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The origin and abundances of the chemical elements revisited

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Summary. The basic scheme of nucleosynthesis (building of heavy elements from light ones) has held up very well since it was first proposed more than 30 years ago by E.M. Burbidge, G.R. Burbidge, A.G.W. Cameron, W.A. Fowler, and F. Hoyle. Significant advances in the intervening years include (a) observations of elemental and a few isotopic ratios in many more extra-solar-system sites, including metal-poor dwarf irregular galaxies, where very little has happened, and supernovae and their remnants, where a great deal has happened, (b) recognition of the early universe as good for making all the elements up to helium, (c) resolution of heavy element burning in stars into separate carbon, neon, oxygen, and silicon burning, with fine tuning of the resulting abundances by explosive nucleosynthesis in outgoing supernova shock waves, (d) clarification of the role of Type I supernovae, (e) concordance between elements produced in short-lived and long-lived stars with those that increased quickly and slowly over the history of the galaxy, and (f) calibration of calculations of the evolution and explosion of massive stars against the detailed observations of SN 1987A. The discussion presupposes a reader (a) with some prior knowledge of astronomy at the level of recognizing what is meant by an A star and an AGB star and (b) with at least a mild interest in how we got to where we currently are.

Key words: Nucleosynthesis – Nuclear reactions – Stars: abundances – Interstellar Medium: abundances – Cosmology – Galaxies: evolution of

1. Preliminary matters

1.1. Historical introduction

Nucleosynthesis, as we now understand it, sprang nearly fully grown in 1957 from the five more or less Jovian foreheads of E. Margaret Burbidge, Geoffrey R. Burbidge, William A. Fowler, and Fred Hoyle (1957; frequently B²FH) and Alastair G.W. Cameron (1957a,b, whose lack of catchy abbreviations can be blamed on the more extensive of his two presentations having remained classified for some years). Neither of these fundamental papers called the subject nucleosynthesis, and just what it should be called took a while to settle down.

Among early writers on the subject, Vernon (1890) spoke of “the genesis of the elements”, Harkins (1917) of “the evolution of the elements”, and German authors of the 20’s (Kuchowicz 1964) of “Synthese von Elementen” and “Synthese des Stoffs”. The English equivalent appears in Atkinson’s (1931) paper “Atomic Synthesis and Stellar Energy” and in Walkes’s (1935) and McCrea’s (1937) discussions of “radioactivity and nuclear synthesis” and “nuclear synthesis and stellar energy”. Nuclear physicists spoke of “transmutation of the elements” (Wilson 1931) or “transmutation of atomic nuclei” (Bohr and Kalckar 1937). Schwarzschild’s (1958) fundamental text endorsed this usage (though he accepted, perhaps reluctantly, a hyphenated “nucleo-synthesis” in his 1962 report for IAU Commission 35, Stellar Constitution). Gamow’s first attack on element formation from a primordial neutron soup (1935) called the process “nuclear transformation”, though Alpher, Bethe, and Gamow (1948, the notorious α , β , γ paper) returned to the descriptive phrase “origin of the elements”.

B²FH entitled their monumental work “Synthesis of the Elements in Stars”, the terminology apparently being Hoyle’s (e.g. Hoyle, 1946, “The Synthesis of the Elements from Hydrogen”), Cameron (1957a,b) seems to have coined the word used in his titles “Nuclear Reactions in Stars and Nucleogenesis” and “Stellar Evolution, Nuclear Astrophysics, and Nucleogenesis”. He stuck by the term for several years (e.g. Cameron 1959) and even briefly made a convert from the other camp, on terminology if not on substance (Burbidge 1960). But the winner was clearly “nucleosynthesis”, the earliest printed appearance of which I have been able to find is Hoyle and Fowler’s (1960) “Nucleosynthesis in Supernovae”. Cameron adopted this usage by the mid 60’s, and it is now nearly universal. The rationale, as explained by W.A. Fowler to graduate students when agreement was still imperfect, is that “nucleogenesis” should be reserved for the process that created the nucleons, while “nucleosynthesis” describes the process of building up heavy nuclides from light ones.

Each of the pioneering papers (B²FH; Cameron 1957) proposed a set of about 10 nuclear processes that could be expected to occur sequentially in stars and to result in the gradual conversion of hydrogen to all heavier elements. These are outlined in Table 1, together with the elements and nuclides that they are expected to produce. Perhaps the most remarkable aspect of the sets of processes is how very close they come to being the set we today regard as both necessary and sufficient to account for the range of heavy elements. Some of the items and terms in the Table require a bit of further explanation. These remarks, unless

otherwise noted, should be taken as applying also to all following sections of this paper.

Table 1. Nuclear processes and products as proposed by B²FH and Cameron

	Processes	Products
hydrogen burning		He ⁴ C ¹³ N O ^{16,17} F Ne ^{21,22} Na
helium burning		C ¹² O ¹⁶ Ne ²⁰ Mg ²⁴
	hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors	He C N O Ne
alpha process		Mg ²⁴ Si ²⁸ S ³² Ar ³⁶ Ca ⁴⁰ Ca ⁴⁴ Ti ⁴⁸
	heavy-ion thermonuclear reactions in orderly evolution of stellar interiors +	
	neutron captures on slow time scale +	Ne to Ca
	hydrogen and helium thermonuclear reactions in supernova explosions	
e-process	statistic equilibrium in pre-supernovae and supernovae	Fe peak
r-process	neutron capture on fast time scale in Type I supernovae	unshielded isobars $A \geq 62$ including actinides
s-process	neutron capture in slow time scale orderly evolution of stellar interiors	most stable isobars $A \geq 62$
p-process	proton capture and photonuclear reactions in Type II supernovae +	excluded/bypassed isobars $A \geq 62$
	photonuclear reactions on slow time scale in orderly evolution of stellar interiors	
x-process	possibly made by nuclear reactions in stellar atmospheres	D Li Be B

1. A nuclide has a fixed value of both N (neutron number) and Z (proton number). Isotopes share a value of Z but differ in N . Isobars share a value of $A = N + Z$.
2. No allowance is made in either scheme for nucleosynthesis in a hot big bang. B²FH were non-believers at the time, while Cameron agnostically remarked on the basis of the wide variations and age dependence of stellar metallicity that “it is tempting to believe that our galaxy may have been originally composed entirely of hydrogen”. Cosmological nucleosynthesis is now generally regarded as important.

3. Hydrogen burning includes the p-p chain, the CN and CNO cycles, and extension to a Ne-Na cycle that occurs at high temperature.
4. B²FH explicitly recognized the uncertainty of the $C^{12}(\alpha, \gamma)O^{16}$ cross section in helium burning and its effects on later stellar evolution and element synthesis. This problem is still with us.
5. Ne²⁰ was assumed to have an excited state with correct even-even spin and parity to give a large cross section for $O^{16}(\alpha, \gamma)Ne^{20}$. This is now known not to be true.
6. Cameron's heavy ion thermonuclear reactions are really the same as B²FH's alpha process, since he pointed out that the first step would be photostripping of alpha particles from some Ne²⁰ nuclei and their subsequent capture by others.
7. Slow (s-process) neutron capture means slower than typical beta decay time scales back to the most stable nuclide at each A value. Such capture will form only the mostly tightly bound nuclide at each A , except where lifetimes are comparable with the time between neutron captures, and branching occurs. Many of these nuclides are shielded from the r-process.
8. The iron peak elements include $A = 50-62$, that is, some or all isotopes of Ti, V, Cr, Mn, Fe, Co, and Ni.
9. Fast or rapid (r-process) neutron capture means time between successive captures that is shorter than typical time scales for beta decay back to the most stable nuclide at each isobar (A value). Thus it proceeds until the next neutron would be unbound, and beta decays back to the most neutron-rich stable isobar occur later. Some of these nuclides also fall in the valley of beta stability traversed by the s-process, but most shield it.
10. The proton or p-process produces the (invariably rare) isotopes with fewer neutrons than those on the valley of beta stability. No element is primarily a p-product, and we have no certain evidence for the existence of its products outside the solar system. It remains uncertain whether the process is primarily one of adding protons or removing neutrons.
11. At the time, Type II supernovae were perceived as being associated with young stars retaining hydrogen (still true) and Type I's as coming from older stars with little residual hydrogen (still true). In addition, the exponential tail of the light curves of SN Is was associated with the half life of Cf²⁵⁴ which had, therefore, to be produced copiously by the r-process in these events. Type II events were blamed for the p-process. Cameron specifically indicates that both types of supernovae should leave white dwarf remnants. B²FH indicate that core collapse is involved but do not specify the remnants.
12. The light nuclides of deuterium, Li, Be, and B are now attributed primarily to cosmic ray spallation in the interstellar medium, with additional input, especially of Li⁷, from big bang nucleosynthesis and (probably) red giant atmospheres.

The years since B²FH and Cameron (1957) laid down the outlines of nucleosynthesis have been marked by relatively steady slow progress and relatively few major disputes in clarifying (a) the abundances of the nuclides in the solar system,

(b) which deviations from these in other stars, gas, and galaxies are real and to be attributed to nuclear (rather than chemical or gas dynamical) processes, (c) the dominant nuclear reactions and their cross sections, and (d) the sites where they occur. These are the primary topics of the sections which follow.

Intermediate progress reports can be found in Ahrens (1968), Trimble (1975), Truran (1984), and Mathews (1988). Rolfs and Rodney (1988) have provided a well-organized textbook introduction to nuclear astrophysics and nucleosynthesis. Of the many conference proceedings, that edited by Arnett and Truran (1985) is outstanding, only partially because Fowler's Nobel Prize was announced during the conference itself.

"Nucleosynthesis" will be used hereafter, without political implications, to mean the building up of heavy elements from lighter ones (and occasionally back again). Creation of neutrons and protons, or at least their excesses over the corresponding antiparticles, is now generally called baryogenesis (rather than nucleogenesis) and will not be further addressed.

1.2. Topics not covered

In order to achieve a complete understanding of the abundances of the elements everywhere and how they got there, we would have to master all of astronomy, from inflation to the great red spot on Jupiter. The present paper falls considerably short of this goal. Last time around (Trimble 1975), I declared out of bounds (a) D/H in molecules, (b) the solar corona/photosphere iron discrepancy, (c) weak He lines in QSO's and the galactic center, (d) peculiar A stars, (e) low energy solar flare particles, and (f) observed galactic cosmic ray abundances, on the grounds that these all reflected primarily non-nuclear processing, including chemical fractionation, ionization-potential dependent effects, incomplete ionization, and spallation (this is, of course, a nuclear process, but not a nucleosynthetic one except for Li, Be, and B). In retrospect, I think each of these exclusions was justified.

This update aspires to be a good deal shorter than the previous 100 pages of nearly 1000 words each. The numbers of astronomers, research programs, and published papers have all grown exponentially with time in the interim (exponential is meant to be a technical term not a pejorative). The universe of discourse is correspondingly further reduced. Subjects that will be addressed not at all or inadequately are listed here, with a few words of explanation in some cases, and references suitable for pursuing them.

1. Surface abundances for white dwarfs, peculiar A stars, hydrogen-deficient, and helium stars, on the grounds that these reflect some mix of diffusion, convection, and accretion of normal gas by the stellar atmospheres, not nuclear processing. This is particularly ungracious of me when one of the supporters of nuclear explanations for Ap stars (Jørgensen 1990) has been so generous in citing my work. For white dwarfs, see Sion et al. (1990) and Wegner (1989), for hydrogen-deficient stars, Hunger et al. (1986), and for chemically peculiar stars of the upper main sequence, Cowley et al. (1986) and Roby and Lambert (1990).

2. Molecules in the interstellar medium, because the chemistry is so fascinatingly complex in its own right that working backwards to atomic and isotopic abundances is almost impossible with few exceptions (Turner 1989; Vardya and Tarafdar 1987).

3. Supernova rates, classifications, and other aspects not intimately related to nuclear reactions and ejection of the products. The subject in general is covered in Petschek (1990; Piran et al. (1990), Woosley (1990), and Wheeler and Harkness (1990). SN 1987A is reviewed by Arnett et al. (1989) and Trimble (1988) and supernova rates by van den Bergh (1990).

4. Stellar structure and evolution, again except as directly coupled to nucleosynthesis. The textbook by Kippenhahn and Weigert (1990) is an excellent place to start. Evolution tracks for intermediate and massive stars have recently been calculated by Castellani et al. (1990), Chiu and Stothers (1990) and Maeder (1990).

5. Stellar populations, that is, categorization of what kinds of stars you find where, and why, apart from their chemical and isotopic compositions. Interesting reviews are those of Hodge (1989) on Local Group galaxies, Frogel (1988) on spheroids, and Gilmore et al. (1990) on the Milky Way. Recent surveys of stellar spectra and velocities and their implications are reported by Morrison et al. (1990), Eggen (1990), Carney et al. (1990), Casertano et al. (1990), Schuster und Nissen (1989), Sommer-Larsen und Zhen (1990), and Fenkart (1989).

6. Nucleocosmochronology is the use of unstable nuclides, primarily the r-process products U and Th and the mixed r- and s-process products Re/Os, Rb/Sm and Th/Nd, to trace out the time scale of nucleosynthesis and the history of galactic massive star formation. It has been superbly summarized by Cowan et al. (1990, 1991). Study of fossil radioactivities (Pu^{224} , I^{129} , Al^{26} , Na^{22} and the like) also belong to this category; a few of them will be mentioned later.

7. Galactic chemical evolution is arguably our ultimate goal – to put together all the processes and sites into a coherent picture of the origins of the time and space dependencies of all abundances. How this might be, in principle, accomplished was first codified by Tinsley (1968, 1980). Recent models have been presented by Edmunds (1990), François et al. (1990) and in Beckman and Pagel (1989). All such models currently suffer from the major defect of having to treat as adjustable parameters several of their major inputs that, in reality, must be physically determined. These include star formation rates, the numbers of stars as a function of mass, and inflow and outflow of gas to and from various regions of the galaxy.

2. Observed abundances

2.1. Solar system (“Cosmic”)

The use of solar system abundances as standard arises from two considerations. First, they can be reliably determined for a much wider range of elements and isotopes than abundances anywhere else. And second, everyone knows that “normal” means as much like oneself as possible. Cameron (1968, 1973, 1982)

was for some years custodian of the official table of cosmic abundances, having inherited it from Suess and Urey (1956) and having now more or less handed it on to Anders and Grevasse (1989).

All of these compilations have drawn on both meteoritic (carbonaceous chondrites) and solar photospheric data as their first choice for elemental abundances. The justification for regarding these as equal primary standards is given in Trimble (1975) and many other places. The normalization between the two is now pinned down to about 5%. Isotopic ratios are much less vulnerable to chemical fractionation and largely come from terrestrial materials for all but the most volatile elements. The near-absence of the noble gases from solids and their non-detectability in the sun arise from the same cause – it is hard to get electrons out of a closed shell. As a result, data for He, Ne, Ar, Kr, and Xe (and to a certain extent H, C, N, and O) are augmented by measurements of the earth's and Jupiter's atmospheres, solar corona and wind, solar energetic particles, and nearby hot stars and ionized gas (HII) regions. For two elements, Kr and Xe, none of these works. They are fitted to adjacent elements, assuming the systematics of the s- and r-processes, and should not be used in testing those systematics (though meaningful isotope ratios come from the solar wind).

Table 2 summarizes “solar system” abundances of those elements and isotope ratios that arise elsewhere in this discussion. Sources are Meyer (1988, elements only) and Anders and Grevasse (1989, elements and isotopes). The numbers are logarithms of numbers of atoms, normalized to Si = 6.00. Isotope ratios are also by number. The final column gives the calculated numbers of atoms in the ejecta of SN 1987A (before, during, and after the event) as presented by Nomoto et al. (1990). This column has been normalized to the others at oxygen, widely regarded as the most abundant product of Type II supernovae and a good tracer of nucleosynthesis in them. It might be reasonable to suppose that other elements for which the 1987A numbers are close to the cosmic ones are co-produced with oxygen.

The table ends with three very small numbers, the abundances (as a fraction of total mass; divide by about 70 to get fractional abundance by number) of the products with $A > 62$ of the s-, r- and p-processes as given by Anders and Grevasse (1989). A surprising amount of attention is devoted to production mechanisms for these given what a very small fraction of the universe is made of them. The attention is a result (a) of their use in various strategies for dating rocks, the solar system, and the history of galactic nucleosynthesis and (b) the existence of a large number of measured cross-sections for neutron capture, which permits very detailed comparison of models with data.

The table does not tell you how much cerium there is in the solar system or the ratio of Ce^{140} to Ce^{142} . If you need to know this sort of thing read Anders and Grevasse (1989) with some care, for the paper is densely packed with details of where the numbers really come from and, by implication, what they can and cannot be used for.

The uncertainties in elemental abundances are at least as large as the differences between the first two columns of Table 2. These arise (apart from the

Table 2. Standard solar system elemental abundances and isotope ratios and calculated SN 1987A ejecta

Element	Isotope ratio	Anders and Grevasse log N	Anders and Grevasse N_i/N_j	Meyer 1988 log N	SN 1987A ejecta Nomoto et al. 1990 log N N_i/N_j	
H		10.446		10.446		
He	D/H	9.435	3.4×10^{-5}	9.447		
	He ³ /He ⁴		1.4×10^{-4}			
C	C ¹³ /C ¹²	7.004	0.011	7.134	6.38	10^{-9}
N	N ¹⁴ /N ¹⁵	6.496	3.7×10^{-3}	6.431	4.69	2.5×10^{-7}
O	O ¹⁷ /O ¹⁶	7.377	3.8×10^{-4}	7.365	7.377	6.7×10^{-9}
	O ¹⁸ /O ¹⁷		2.0×10^{-3}			5.9×10^{-3}
F		2.926		2.926	-2.98	
Ne	Ne ²¹ /Ne ²⁰	6.537	2.4×10^{-3}	6.519	6.51	1.3×10^{-3}
	Ne ²² /Ne ²⁰		0.073			0.128
Na		4.759		4.763	4.10	
Mg		6.031		6.029	6.28	
Al		4.929		4.929	5.16	
Si		6.000		6.000	5.96	
P		4.017		4.017	3.93	
S		5.712		5.653	5.28	
Cl		3.719		3.716	2.66	
Ar		5.004		5.029	4.46	
K		3.576		3.580	2.34	
Ca		4.786		4.799	4.32	
Sc		1.534		1.531	-2.36	
Ti		3.380		3.431	3.02	
V		2.467		2.470	1.50	
Cr		4.130		4.117	3.67	
Mn		3.980		3.940	3.02	
Fe		5.954		6.041	5.55	
Co		3.352		3.352	2.25	
Ni		4.693		4.693	4.78	
Cu		2.718		2.690	1.17	
Zn		3.100		3.045	2.11	
s-process		2×10^{-7}	by mass			
r-process		1×10^{-7}	by mass			
p-process		4×10^{-9}	by mass			

difficult volatile elements) from discordances at the 0.1–0.3 dex level between meteoritic and solar values and comparable probable errors in the oscillator strengths (gf values) needed to derive the solar photospheric abundances, according to Grevasse (in Herstmonceux 1990).

The custom of ordering lists like Table 2 to follow the periodic table makes it tricky to see which are really the commonest elements. Going again by numbers of atoms, a common-to-rare list would begin H, He, O, C, Ne, Mg, Si, Fe, S, Ar, Al, Ca, Na, Ni, Cr, P, Mn, Cl, Ti, Co, and Zn.

2.1.1. Solar system anomalies

The solar system number whose significance is most often questioned is the D/H ratio. About the same value can be extracted from solar wind and meteoritic components, assuming that all the deuterium in the sun has been burned through to He³ (which, in turn, has partially survived). But it is larger than the D/H = 1–2 × 10^{−5} in the present interstellar medium and arguably reflects some chemical fractionation during the formation of the solar system. The effects of this particular uncertainty on our interpretation of cosmological nucleosynthesis are luckily rather minor.

Much more complicated is the pattern of isotopic anomalies found in small, rather rare, meteoritic inclusions. “Anomalies” in this context means deviations from solar system average that cannot be explained by mass-dependent (chemical etc.) fractionation, radioactive decays, or impacts of cosmic rays and solar energetic particles. The elements and isotopes affected are (at least) O¹⁶, Ne²², Mg²⁶, Si, Ar, the heaviest isotope each of Ca, Ti, and Cr; Kr, Sr, Te, Xe, Sc, Ba, Nd, and Sm.

The xenon anomalies, Mg²⁶ and Ne²² can be fit by patterns of decay of the extinct unstable nuclei I¹²⁹, Pu²⁴⁴, (which fissions to a range of Xe isotopes), Al²⁶, and Na²². The initial deduction was that the progenitors must have been incorporated into the meteoritic sites where we now find them within a few half-lives of synthesis. Hence the meteorites solidified within 10⁸ yr (I¹²⁹ and Pu²⁴⁴) or 10⁶ yr (Al²⁶) or 2 yr (Na²²) of the last nucleosynthetic input to the protosolar gas.

The very short half life of Na²² casts doubts on this whole scheme. Furthermore, significant anomalies with patterns that repeat from sample to sample in O¹⁶, Ca⁴⁸, Ti⁵⁰, and Cr⁵⁴ cannot be explained this way, since none has a radioactive progenitor; and they must have been made as O, Ca, Ti, and Cr, not something else. The alternative is that grains solidify close (in space and time) to the supernovae and so forth that produce assorted heavy elements. Detection of dust in ejecta from novae and SN 1987A strengthen this interpretation. The grains must then retain their identities through interstellar medium and protosolar nebula and into the carbonaceous chondrites. An anomalous inclusion then simply preserves nucleosynthesis patterns in a particular object, whose products would have to be averaged with many other supernovae (etc.) to get the solar system average.

Donald D. Clayton was already a strong advocate of such pre-solar grains at the time of the 1974 NATO conference (Trimble 1975), while most other participants expressed considerable scepticism. The idea is now so much a part of the conventional wisdom that no special mention of it is thought necessary in typical discussions of the anomalies (Niemeyer 1988; Hartmann 1988), though mercifully Clayton’s choice of a name for the grains, SUNOCONS (for SuperNOva CONDensateS) does not seem to have caught on.

With the acceptance of pre-solar grains as the carriers of the anomalies, focus has shifted to trying to understand the nuclear processes and sites responsible for them. The excesses of Ca⁴⁸, Ti⁵⁰, and Cr⁵⁴, for instance, seem to be the

products of nuclear statistical equilibrium (e process) in a site with unusually many neutrons (Niemeyer 1988; Hartmann 1988). Particularly intriguing is the probability that Ne, Ar, Kr, and some Xe anomalies in SiC inclusions are s-process products (Lewis et al. 1990; Gallino et al. 1990). If so, then the excess Ne^{22} was made as neon not as sodium, and the most puzzling of the time scales goes away. As still further anomalies are recognized, focus will undoubtedly shift again to the problem of self-consistently making all the strange isotopes found in a particular chemical setting at the same time and in a way that makes sense for the inclusion chemistry.

Finally, one must ask whether solar system abundances are, in fact, representative of the space-time volume 4.65 Gyr ago and 6–10 kpc from the galactic center. The strongest evidence for is that most stars turn out “normal” when the assumption is made. The nagging evidence against is the difficulty of finding any bit of interstellar gas at any temperature with metallicity as high as solar. Abundances of individual heavy elements in cool gas phases range downward from solar to 0.01 solar or less (Cowie and Songaila 1986 and references therein). The standard interpretation, depletion on grains, is strongly favored by correlations of abundance discrepancy with condensation temperature. About half the heavy elements must be locked up in grains, with the behavior of oxygen dominating just because there is so much of it.

But the deficit persists in large HII regions where one would have expected grains to be largely evaporated away. Orion, for instance, has $Z = 0.013$ and $Y = 0.26$ on the scale where solar values are 0.02 and 0.28 (Ferland in Hermonceux 1990). And other HII regions are much the same (Scheffler and Elsässer 1987). The issue has been raised, and quietly lowered, a number of times before, and I do not know the correct answer. At any rate, a metal rich sun would have had an easier time than its contemporaries in forming terrestrial planets, so we should perhaps have expected something of the sort.

2.1.2. All other anomalies

Table 3 summarizes (in a surely not unbiased way) extra-solar system deviations from normal abundances that I believe are both reasonably well established and trying to tell us something about nucleosynthesis and galactic chemical evolution.

2.2. *Other galactic stars*

Two sorts of deviations of stellar abundances from solar count as interesting for our purposes. First, ones that reflect the composition of the gas from which the star originally formed tell us about previous nucleosynthesis and chemical evolution. Second, ones that reflect nuclear reactions (and usually mixing and mass loss) in the stars themselves tell us about future nucleosynthesis and chemical evolution. The distinction matters only when one thinks that what is going on has changed significantly in the stretch of gigayears under consideration. For

Table 3. Interesting deviations from solar system abundances

What	Where	Which way	How much
He/H	old stars	<	ΔY to -0.06
	ISM of dwarf galaxies		ΔY to -0.06
	evolved stars		to $Y = 1$
	planetary nebulae	>	factor 2–10
	supernova remnants		factor 2–10
Li	Population II stars	<	factor 10
	some carbon stars	>	factor 100
Li Be B	cosmic rays	>	factor 10^6
average Z or $[\text{Fe}/\text{H}]$	Pop II stars, dwarf galaxies, qso absorption lines	<	factor $10-10^4$
	nuclear bulge stars	>	factor 1.5–3
	giant E's		
CNO ratios	evolved stars, PNe, SNR		
	N/C	>	factor 2–10
	$\text{C}^{13}/\text{C}^{12}$	>	factor 10–20
	N/O	>	factor 2–10
s-process	subset of above	>	factor 10^{2-3}
	evolved stars	>	factor 10^{2-3}
O/Fe	Pop II stars	<	factor 3–30
	Pop II stars	>	factor 1.5–20 correlated with $[\text{Fe}/\text{H}]$
O, S, Ar	Type II SNe, SNR	>	factor 10–10,000
Ni^{56} , Co^{56}	SN 1987A	>	unstable
Fe	Type I SNe, SNR	>	factor $10-10^5$
r-process	very metal poor Pop II	<	factor ≥ 10

instance, the mix of s-process products seen in cool, evolved stars getting ready to shed planetary nebulae now is presumably a pretty good guide to the mix of s-process products shed in past planetary nebulae, at least as far back as stars had about the same amount of iron (etc.) atoms to capture neutrons as they have now.

The standard notation for discussing deviations from solar system composition is $[M/\text{Fe}]$, which means the logarithm of the ratio of the number of M atoms to the number of Fe atoms in the star (etc.) in question divided by the same ratio in the sun. M is not a particular element; it is used generically to mean other metals. For instance, a star with $[\text{Fe}/\text{H}] = -2.0$ has only 1% as many iron atoms as the sun does. A star with $[\text{Fe}/\text{H}] = -2.0$ and $[\text{O}/\text{Fe}] = +0.5$ is deficient in both Fe and O, but while Fe is down by a factor 100, O is down only by 30.

$[\text{Fe}/\text{H}]$ is often treated as a short hand for overall metal abundance, historically because of the prominence of iron lines in the visible spectra of cool stars. It is a poor surrogate because the most abundant heavy elements, O, C, Ne, and N (yes, astronomers still call these metals) do not vary in lock step with iron, especially at values of $[\text{Fe}/\text{H}]$ less than -1.0 .

2.2.1. Unevolved stellar compositions

Normal composition is very common and seems to describe most of the stars in the solar neighborhood that fully share disk rotation. It is, therefore, somehow boring and gets very little attention, even here, except to remark that recent studies of nearby normal B stars have confirmed the agonizingly-extracted solar system argon abundance as $\log N(\text{Ar}) = 6.5$ (Holmgren et al. 1990; Keenan et al. 1990).

The most conspicuous deviation from solar composition is the deficiency of everything except hydrogen (and presumably helium) in virtually all stars that do not share galactic disk rotation. This includes both globular cluster members and field halo stars. The exact values of these deficiencies spent many years mired down in squabbles between photometrists and spectroscopists, but have now largely been sorted out by proper allowance for continuous absorption. Contrary to what you might have guessed, the photometrists were more nearly correct. Deviations from local thermodynamic equilibrium still lead to discrepancies for iron itself between determinations based on FeI and on FeII lines (Bikmaev et al. 1990) which get worse at low values of $[\text{Fe}/\text{H}]$.

Most globular clusters fall in the range $[\text{Fe}/\text{H}] = -0.5$ to -2.0 (continuing to use our misleading surrogate). At the extremes, NGC 6553, near the galactic center, may not be metal deficient at all (Ortolani et al. 1990), and NGC 5053 may come as low as -2.58 (Wheeler et al. 1989). There is a good deal of correlation of composition with position, the less deficient clusters and stars lying systematically closer to both the galactic center and the galactic plane (Zinn 1985; Lewis and Freeman 1989), though out beyond twice the solar circle or thereabouts, any systematic trend for the clusters seem to vanish in (real) scatter. Almost ubiquitous uniformity of composition within each cluster is a strong argument against self-enrichment (Murray and Lin 1990).

Field stars extend to considerably lower metallicities than the clusters, the record $[\text{Fe}/\text{H}]$ is -4.25 ± 0.05 for the giant CS 22885 (Molari and Bonifacio 1990) and the main sequence double-lined spectroscopic binary CS 22876-32 (Nissen 1990; Molari and Castelli 1990). Correlation of composition with kinematics as well as with location in the galaxy is well established. Whether all quantities vary smoothly or group themselves into two or three discrete populations is currently a topic of much acrimony (stellar population references mentioned in Sect. 1.2).

Statements about the compositions of these halo field and cluster stars other than their general metal deficiency must be uttered with much less confidence, though I would not still stand by my 1975 scots verdict of “not proven”. Wheeler et al. (1989) have discussed the evidence with some care, and to their remarks can be added those of G. Smith, P. Nissen, B. Gustafsson, and P. François (in Herstromceux 1990), the papers of Peterson (1990), Brown et al. (1990a) and Adelman and Phillips (1990), and the review by Gustafsson (1989).

The best-established deviation from uniform metal deficiency in Population II stars is $[\text{O}/\text{Fe}] \approx 0.5$. The range of values found, 0.3–0.7, is comparable with the error bars, and inverse correlation with $[\text{Fe}/\text{H}]$ is probably real but not yet highly significant. This oxygen excess (or underdeficiency) is important for two

reasons. First, it tells us something about the order in which the Milky Way became enriched in various heavy elements. Second, including the correct amount of oxygen in calculations of evolutionary tracks of globular cluster stars lowers cluster ages by a couple of Gyr, thereby reducing the strain on cosmologists who need to make the universe old enough to accommodate them.

Other elements arguably underdeficient in these stars include calcium and silicon and perhaps other alpha-particle nuclei. There is some evidence for odd- Z elements (e.g. Na, Al) being more deficient than even- Z (e.g. Mg). Carbon, on the other hand, tracks iron much better than oxygen, with underdeficiency reaching perhaps $[C/Fe] = +0.3$ at $[Fe/H] = -2$. Field and globular cluster stars display the same trends.

The best-established over-deficiency is that of elements heavier than iron, though only a few are really measurable at the lowest $[Fe/H]$ levels. Typical numbers below $[Fe/H] = -2.0$ are $[Ba/Fe] = -1.0$, $[Eu - La/Fe] = -0.4$, and $[Sr - Y - Zr/Fe] = -0.3$. The patterns are well fit by the assumption that, in this metallicity range, the very heavy elements consist entirely of r-process products. This makes sense, because the s-process can operate only when a star is born with some heavy elements to act as seeds for neutron capture, while the r-process can (probably) work with iron made in the star itself, even if $Z = 0$ to begin with. Below $[Fe/H] = -2.5$, even the r-process elements may be deficient.

Nitrogen is seemingly also a secondary element, that is, one that can only be produced (by CNO cycle hydrogen burning) in stars that already have some metals. Its behavior in evolved stars and in the interstellar medium (below) confirms that this is so at the present time. But among population II stars, nitrogen is not systematically overdeficient. Rather $[N/Fe]$ scatters widely with an average near zero and only weak correlations with anything. It is possible, however, to turn two weakish trends into one stronger one in which $[N/C]$ drops from zero to perhaps -0.6 as Fe/H falls from 0 to -2 .

Beryllium tracks iron down to $[Fe/H] = -1$, below which it is too weak to measure reliably (Ryan et al. 1990, Vangioni-Flam et al. 1990) indicating that most of what we see is not a hot big bang product, but is rather co-produced with other heavy elements.

Lithium, on the other hand, has a floor abundance of $\log N(Li) \approx 0.5$ ($[Li/H] = -1.0$) in population II stars with surface temperatures such that convection should not have taken it into (and therefore out of) circulation. This component (Spite and Spite 1982; Pagel 1991) very probably does remain from hot big bang nucleosynthesis and has proven a strong constraint on cosmic baryon density. As a result, stellar structure theorists have been throwing gobs of lithium at each others' stars to see whether it will stick to the surface or be consumed. At the middle of the 7th inning (Deliyannis et al. 1990, Dearborn and Hawkins 1990) it is sticking, so that the floor value remains cosmologically meaningful.

Stars more metal rich than the sun have many fewer admirers (or at any rate authors and papers) than the metal poor ones. Such stars are rather difficult to find, even when and where you would expect them. Among thirteen young star clusters, Nissen (1988) found twelve indistinguishable from solar at the one-sigma

level, plus IC 4651 at $[\text{Fe}/\text{H}] = +0.18 \pm 0.05$. The nearby strong-CN (“super metal rich”) stars identified by Spinrad and Taylor (1969) remain something of a puzzle. They can be regarded as having strayed into the solar neighborhood from the last generation of star formation in the nuclear bulge (Grenon 1989), but their co-discoverer (Taylor and Johnson 1987) is still not absolutely certain that their strong lines (largely CN, CH, and highly damped lines of CaI, MgI NaI, and FeI) cannot be explained by peculiarities of atmospheric structure. R. Peterson (in Herstonceux 1990) thoroughly confused me by reporting that the SMR stars probably have $[\text{O}/\text{Fe}] > 0$, a trait usually associated with metal poor stars.

Unambiguously metal rich stars are found at least one place in the Milky Way – near the center. The M giants in Baade’s window, for instance, come in at $[M/\text{H}] = +0.5$ (Sharples et al. 1990), a reasonable extrapolation of gradients measured further out.

Three communal properties ought to be extractable from these data on individual stars. These are metallicity as a function of position in the galaxy (whose general trends have already been mentioned), metallicity as a function of time, and numbers of stars as a function of metallicity.

Temporal evolution is clearly present in the contrast between old, metal-poor halo stars and young, metal-rich disk stars. Beyond this, seeing correlations requires something of an eye of faith. Pagel (1988) reproduces a diagram showing quite persuasive increase of $[\text{O}/\text{H}]$ with time; Wheeler et al. (1988) show essentially a scatter diagram, at least for disk stars. Scatter is large for clusters as well as individual stars. For instance, Richtler and Kaluzny (1989) report $[\text{Fe}/\text{H}] = -1.0$ in the open cluster NGC 2112 slightly younger than the sun, while NGC 188, somewhat older, is deficient in neither metals nor helium (Caputo et al. 1990). The standard interpretation is that the enrichment of the disk in the last 5–10 Gyr is simply too small to dominate the variations in initial stellar composition associated with formation at different places in the galaxy, on large or small scales (Boesgaard 1989).

Finally, counting stars in the solar neighborhood as a function of metallicity leads to the classic G dwarf problem – fewer metal-poor stars than simple minded but reasonable models predict – which has inspired a large fraction of the modellers of galactic chemical evolution over the past 20 years. The problem persists for the solar neighborhood even when the more fundamental index $[\text{O}/\text{H}]$ replaces $[\text{Fe}/\text{H}]$, but does not exist in other regions, including the globular cluster populations and the giants in Baade’s window (Pagel 1989). If you would like a fair chance at picking the correct solution take any two of the following: variable initial mass function, infall, outflow, prompt initial enhancement, metal-enhanced star formation, intermediate thick disk population, bimodal star formation.

2.2.2. Evolved stellar compositions

The observational picture is easiest to follow if a theoretical curve is first drawn to “guide the eye.” Glance back at Table 1, keeping in mind two bits of stellar structure and evolution theory. First, the CNO cycle is responsible for most

of hydrogen core burning in stars above about $1.5 M_{\odot}$ and for shell burning at all masses. Second, nuclear reaction products get to the surface only if carried by convection, meridional circulation, or something. Convective dredge-up is possible during three evolutionary phases (not all of them in stars of all masses) set forth by Iben and Renzini (1983). Transport by meridional circulation was predicted by Paczyński (1973) for main sequence B stars. “Or something” mostly means mass loss that uncovers layers we would not otherwise see.

Beginning with the least evolved stars, enhanced nitrogen in main sequence B stars, presumably attributable to meridional circulation, has now been seen (Mathys 1990; Lyubimkov 1990). In the same mass range of $5\text{--}20 M_{\odot}$ excess sodium and $\text{Mg}^{25,26}$ also appear quite close to the main sequence, and hence presumably as a result of the first dredge-up phase (Denisenkov 1990). The surprise is not so much the mixing as that a hydrogen burning zone should be hot enough to reach a Ne-Na cycle this early in stellar life.

CNO and their isotopes should be seen to be modified from the giant branch onward and are, though not always in precisely the expected patterns (Wheeler et al. 1989 and references therein). In general, anomalies are stronger and set in earlier than dredge-up theory forecasts, as if additional (meridional, semi-convective...) mixing were important. Interesting stars are easier to pick out in globular clusters, because the HR diagram tells you which ones to look at first, but strong CN, enhanced $\text{C}^{13}/\text{C}^{12}$, and, at later stages also decreased $\text{O}/(\text{C}+\text{N}+\text{O})$ are common to the clusters and to the field (Pilachowski et al. 1990; Bell et al. 1990; Smith and Mateo 1990). The excess helium that should also arise from hydrogen burning is difficult to spot in cool giants, but is there in the nitrogen-enhanced massive stars near the main sequence (Lyubimkov 1990).

The flash with which helium burning begins in low mass stars is a possible occasion for sudden, extensive mixing, but calculations do not yet tell us how much of what should end up at the surface. The state of the art on peculiar stars from this evolutionary phase onward appears in the volume edited by Johnson and Zuckerman (1989).

The second ascent of the red giant branch heralds “third dredge up”, during which we expect to see products not only of hydrogen burning but also of helium burning and the s-processing that occurs when H-burning, He-burning, and convective shells chase each other back and forth inside the star (Iben and Renzini 1983). The resulting carbon enhancement is the only abundance anomaly dignified by its own spectral classes, the R, N, and S stars. This happens because CO soaks up most of whichever element is less abundant, so the boundary from $\text{C}/\text{O} < 1$ to $\text{C}/\text{O} > 1$ makes for an abrupt change in the molecular species that dominate cool star spectra.

Carbon excesses are also a feature of the related BaII stars (population I), CH subgiants (Population II), and R CrB stars (in which carbon can make up 10% or more of the atmosphere, and hydrogen is entirely gone). Some carbon stars carry traces of their origin in the form of outer envelopes or dust layers where oxygen still predominates (LeBetre et al. 1990; Lambert et al. 1990).

Excess carbon is regularly accompanied by (and, in the transitional spectral type MS, preceded by) excesses of barium and other s-process elements in the

expected ratios (Gustafsson 1989; Jäschek and Keenan 1985). A spectacular example of the transition is the peculiar supergiant FG Sge. Since 1894 it has cooled from A5I to G5I, and, in the early 1970's, its spectrum sprouted strong lines of the heavy elements from Y to Sm (Herbig and Boyarchuk 1968; Langer et al. 1974), implying excesses of factors of 20–30 over solar abundances. A second helium flash seemed a likely mechanism, since the star already has a planetary nebula around it. Some of the heavy element lines have continued to strengthen and others have appeared (Cowley et al. 1985; Wallerstein 1990), so that the star is now greatly overstocked not just with the standard s-process peak elements around Zr and Ba (Smith 1984) but also with the lanthanides, represented by ions from LaII to GdII. Eu and Gd are normally counted as r-process, their dominant isotopes being more neutron rich than the valley of beta stability reached by slow neutron capture.

We do not understand what is going on in FG Sge, but it is a lot of fun to watch. HD 108317, by contrast, has apparently had strong EuII and LaII lines all our lives (if not all of its), leading Lambert (in Herstmonceux 1990) to ask whether there might be a category of stars with surface r-process excesses. He did not answer the question.

Another interesting special case includes the BaII (giant) stars, which seem all to be close binaries, prompting the interpretation that the s-processing occurred in an initially more massive companion whose white dwarf corpse still circles the remaining giant after polluting it (Malaney and Lambert, 1988).

Because Population II stars start life deficient in carbon and other heavy elements, enhancements due to their own nuclear reactions show up more readily. The ratio of C to M giants varies with local [Fe/H] around the Milky Way and from galaxy to galaxy just as you would expect from this consideration. And [Ba/Fe] is anti-correlated with [Fe/H], opposite to what happens in unevolved stars (Fernandez-Villacañas et al. 1990).

Unstable technetium (Merrill 1952) was the first indicator of in situ nucleosynthesis in asymptotic giant branch stars. S-type stars with otherwise similar abundance patterns may or may not show Tc, leading Brown et al. (1990) to propose that those without are binary components that acquired their anomalies by mass transfer, while Tc-positive stars made their own.

Some of these cool, evolved giants show lithium lines indicative of undisturbed Population I abundances ($\text{Li}/\text{H} \approx 10^{-9}$) up to 100 times that (Boesgaard 1970; Lambert 1985; Smith and Lambert 1989). Because the material now at their surfaces has been cycled through hydrogen-burning zones, their initial lithium has presumably been destroyed and replenished by reactions in the stars themselves (Gustafsson 1989; Lambert 1985). The amount that can survive to be ejected is uncertain, but it is widely believed that these stars are part of the x-process, making the Li^7 that cannot be accounted for by the early universe or by cosmic ray spallation (whose contributions is deducible from the amount of co-produced Li^6 (Rebolo 1989)).

Most asymptotic giants and related stars show evidence of current mass loss in winds. This is presumed to progress to a superwind and so (perhaps via OH/IR stars) to a planetary nebula. Hence the excess nitrogen, C^{13} , and s-

process material that we see, along with helium that we don't, will be returned to the interstellar medium over the 10^{8-10} yr lifetimes characteristic of stars too low in mass to give rise to supernovae.

Very massive stars can also display pre-terminal abundance anomalies and mass loss indicative of nucleosynthesis and chemical evolution under way. Among the Wolf-Rayet variables, mass loss has already removed all the hydrogen, and we are seeing helium layers with major enhancements of carbon, nitrogen, and oxygen (in proportions that are reflected in spectral types WC, WN, etc. and may constitute an evolutionary sequence). A ratio of C/He in excess of 0.1 is sometimes achieved (Hillier 1989), and the most vigorous of these stars can strip themselves even of their helium layers (Dopita et al. 1990). Anne Underhill (1988) does not believe a word of this, and I admire her persistence without in any way desiring to emulate it.

Population considerations dictate that only stars initially exceeding $40 M_{\odot}$ or thereabouts are as profligate with their products as WR stars, so they probably are too rare to dominate the production of any particular element or nuclide. But stars near $20 M_{\odot}$ do the same thing on a more modest scale. Among the many useful results of detailed analysis of SN 1987A and its progenitor are the conclusions that it had shed several solar masses of material enriched in (at least) nitrogen and helium prior to explosion and that the residual envelope was also considerably enriched in He (Arnett et al. 1989). The evidence includes narrow infrared and ultraviolet lines illuminated at various stages and the shape of the early supernova light curve.

2.2.3. Stellar ejecta

2.2.3.1 Planetary nebulae. Planetary nebulae provide several kinds of information (Clegg 1989). Their over-abundances of He, N, C, and (perhaps) O and Ne tell us directly what has been produced in the progenitor star and ejected. What we hear is consistent with the message of the AGB stars of the previous section. The mass of the central pre-white-dwarf reveals (modulo some theory on how big stellar cores get) the initial mass of the star responsible, and thus the length of time since that star formed. The amounts of elements that are not affected by hydrogen and helium burning can, therefore, be used to trace out abundances as a function of both space and time. The ionized hot gas allows us to see lines of Ne, Ar, Cl, and other elements virtually undetectable in old, cool stars.

Excess helium and nitrogen are common (Frietas Pacheco et al. 1989) and largest in nebulae with the most massive progenitors. Carbon enrichment is common but missing from objects with progenitors too small to have experienced third dredge-up (Peña et al. 1990). Just as anomalies in evolved stars tend to set in a bit earlier and be a bit more extreme than you would have predicted, some planetaries reveal unexpectedly extensive nuclear processing in the form of enhanced neon, and nitrogen that must have come from the ON part of the CNO tricycle (Henry 1990). An implication is that O-Ne-Mg white dwarfs that we know exist among cataclysmic variables can probably also form in single stars. As in the AGB stars, a mix of carbon-rich and oxygen-rich dust can reveal stages in the stripping of the star (Zhang and Kwok 1990).

Heavier element abundances as a function of progenitor star mass indicate that O and Ne grew fastest in the young Milky Way, then S and Ar, and Fe most slowly (Maciel in Herstmonceux 1990). Galactic gradients in the abundances of elements not synthesized in the progenitors show up at the level of a factor of two over $R = R_0 \pm 50\%$ (Clegg 1989; Clegg in Herstmonceux 1990).

2.2.3.2 *Novae*. The composition of nova ejecta is primarily of interest to people modelling the explosions. Spectra reveal that there are systems with each of the three main expected types of white dwarf interiors – He, C+O, and O+Ne+Mg, and perhaps Fe as well (Prialnik et al. 1989; Starrfield 1988) – and that some of the interior stuff gets mixed in with the accreted stuff and blown off. Novae are too rare for this to be an important contribution to nucleosynthesis of the dominant elements and isotopes. But hydrogen burning there does get unusually hot and often proceeds only as far as the capture of a single proton, leading to the suspicion that there could be significant input of odd-A isotopes of N, O, F, and Ne. No observational approach can currently test this suspicion, which remains much as it was 15 years ago.

More recently novae have been implicated as a contributor of Al^{26} to the interstellar medium, and so, presumably, to the solar system, where it lingers as isotopically anomalous Mg^{26} in meteorites, after having perhaps heated the meteorite parent bodies. The subject is currently in some disarray because of detection of gamma rays from Al^{26} decay in (a) the general interstellar medium or (b) mostly the region around the galactic center or (c) the very local interstellar medium, depending on which pundit you trust (Blake and Dearborn 1989). Production of Al^{26} in novae has, at any rate, the observational virtue of giving roughly the right distribution on the plane of the sky (Higdon and Fowler 1989), though the number of resolution elements in the data is very small. Data from the Gamma Ray Observatory are expected to clarify considerably the amount and location of Al^{26} in the galaxy as well as a number of other issues concerning production of unstable nuclides (Gehrels and Share 1989). If you would like to test your own Al^{26} generation mechanism, the half life is about 700,000 yr, and any distribution except the very local one requires a current galactic supply of about $3 M_{\odot}$.

2.2.3.3 *Supernovae*. Supernovae are surely the key to most of nucleosynthesis and galactic chemical evolution. They and their progenitors are supposed to be responsible for most of hydrostatic heavy element production, nearly all of explosive nucleosynthesis, the ejection of the products of both, and a large fraction of the stirring of interstellar gas that mixes everything together. We have all believed this at least since B²FH and Cameron (1957) told us about it. Nevertheless, my supernova remnant section fifteen years ago ended somewhat plaintively “Still, it would be nice to have direct evidence that supernovae really do make a range of heavy elements.”

We now have that evidence (Danziger and Bouchet 1989). And it fits into a coherent picture if we make the conventional assumptions that the progenitors of the Crab Nebula and Cas A were stars of $8\text{--}10 M_{\odot}$ and $\gtrsim 30 M_{\odot}$ that underwent

core collapse as Type II supernovae, while Tycho, Kepler, and SN 1006 were Type I events with low-mass progenitors and no hydrogen in their spectra (if anyone had thought to photograph them!). The Crab is definitely helium rich, and probably patchily so (MacAlpine 1989). My refusal to believe that the strong Ni lines mean $[\text{Ni}/\text{Fe}] \geq 0.6$ is probably sheer pigheadedness (Hudgins et al. 1990).

The optical counterpart of Cas A includes three dynamically distinct classes of gas blobs: fast knots with lots of O and its burning products S and Ar, quasi-stationary flocculi with only He and N detectable, and fast-moving flocculi of H with excess N (Fesen et al. 1988). These come apparently from inner, middle, and outer layers of the progenitor.

The “best buy” model for classical Ia events illuminates them with $0.5\text{--}1.0 M_{\odot}$ of newly-synthesized Ni^{56} , which beta decays to Co^{56} and then Fe^{56} (Wheeler and Harkness 1990). The latter has much the same half life as the Cr^{254} formerly entrusted with the job. Excess iron has been reported in two of the three putative galactic SNI remnants, Kepler (Hatsukade et al. 1990) and 1006 (Hamilton and Fesen 1988), though the amount emitting at the wavelengths studied is still considerably less than is needed to power the light curve, and Tycho remains undetected in X-ray iron lines (Teske 1990). Of the other elements that ought to come out of SNI explosions, Ne and Mg are overabundant in Tycho by factors of 10 and 100, while Kepler has extra Si, S, Ar, and Ca by factors of a few to 20 as summarized by Hillebrandt (in Herstmonceux 1990). The data for the heavy elements in SNI remnants come primarily from X-ray spectra, and having to figure out the correct allowance for non-equilibrium ionization has made them difficult to extract and rather uncertain.

Supernovae and remnants in other galaxies help to fill in the picture. Spectrum synthesis (Wheeler and Harkness 1990) applied to SN Ia 1981B reveals Fe, Ca, S, Si, Mg, and O near maximum light and forbidden $[\text{FeI}]$ and $[\text{CoI}]$ somewhat later. Line profiles are of the P Cygni type with maximum velocity near $10,000 \text{ km s}^{-1}$. Assumption of the relative abundances expected from deflagration (rather than detonation, which burns everything up to the iron peak) of C and O leads to the right relative line strengths.

The pulsar-harboring remnant 0540-63 in the Large Magellanic Cloud has excess Ar and S, presumably from an oxygen-burning zone of a massive star (Kirshner et al. 1989). The SN II 1957D in M83 has been recovered (Long et al. 1989), and its ejecta are dominated by O and S. SN 1983N was a Ib event, requiring a smaller amount of Ni^{56} decay to account for its exponential light curve than do the Ia's. The intensity of an infrared $[\text{FeII}]$ line implies about $0.3 M_{\odot}$ of new iron, which is just right (Graham et al. 1985). Finally, the first extragalactic supernova ever studied, SN 1885 in M31 (S And), has been recovered in absorption against a background source, and it too has some excess iron (Fesen et al. 1989a). The light curve rose and fell with extraordinary rapidity, and the type is anybody's guess (de Vaucouleurs and Gorwin 1985).

Most informative of all has been SN 1987A in the Large Magellanic Cloud. It is sometimes a little difficult to say where observations leave off and theory begins. Probably the right way to describe the situation is that the firm evidence

for about $0.07 M_{\odot}$ of fresh Ni^{56} and a solar mass or so of new oxygen calibrates and adds credibility to the details of the models. The evolution of the progenitor and the early part of the light curve are most readily fit by an envelope with nearly half its mass in helium and a good deal of pre-terminal mass loss (Eastman and Kirshner 1990). At least a couple of solar masses of new He are implied, and $\Delta Y/\Delta Z$ is 2.5–3 in Woosley's models (Arnett et al. 1989), though somewhat lower in another set (Thielemann et al. 1990). This is a considerable change from epoch 1975, when massive stars were widely believed to produce almost no helium (though I have always believed that massive, metal-poor stars would be different; Trimble et al. 1973; Dearborn and Trimble 1980). The pre-explosion wind was also nitrogen-rich, relative to hydrogen (not relative to other heavy elements made in massive stars).

The amount of newly-synthesized Ni^{56} was first calculated as $0.07\text{--}0.08 M_{\odot}$ from the brightness of the exponentially-falling light curve and later confirmed by detection of gamma rays characteristic of $\text{Co}^{56} \rightarrow \text{Fe}^{56}$ and infrared lines from CoII . Both have now faded away over several of the 77-day half lives of Co^{56} . The fading has revealed fainter but longer-lived infrared lines of Co^{57} . About $0.003 M_{\odot}$ of Ni^{57} must originally have been there, so that the final ratio of Fe^{56} to Fe^{57} will be quite close to solar (Varani et al. 1990). We can now say with some confidence that iron-peak nuclides do not come primarily from Type II supernovae.

Above all else, SN 1987A ejected oxygen, something like $1\text{--}3 M_{\odot}$ (Danziger 1990). This is perhaps enough to tell us that the cross section for $\text{C}^{12}(\alpha, \gamma)\text{O}^{16}$ must be at the high end of the laboratory range. C, Mg, Si, Ar, Ca, and (stable) Ni, and probably other elements in the C-Zn range are also present in roughly the expected amounts (cf. Table 2) or at least ratios. The analysis is complicated by the fact of never having all the gas both optically thin and ionized at once (Danziger 1990; Frietas Pacheco 1990). The case for excess barium has probably to be regarded as unproven, and no elements that come primarily from the r-process have yet been seen.

The supernova acted as a continuum source against which absorption from interstellar gas in its galaxy and ours could be seen. The abundance patterns, as is the case for cool gas in the Milky Way, are dominated by depletion on grains, not nucleosynthesis. This, I fear, may also be so for the upper limit on lithium, $\text{Li}/\text{H} \leq 1.6 \times 10^{-10}$ (Sahu in Herstmonceux 1990). In any case, we probably do not know enough about the astration history of the gas to use the limit to settle existing disagreements about the primordial abundance of lithium.

2.3. Interstellar matter and the cosmic ray source composition

The chemical composition of the interstellar medium ought to be a very important input to models of chemical evolution, for it represents $t = \text{now}$ in the $Z(t)$ curve. In practice, it wasn't in 1975 and it isn't now. We see the full complement of heavy elements in gaseous, atomic, interpretable form only when all the grains have been vaporized. It is not certain this ever happens. Even Orion and other large HII regions reveal slightly less than solar amounts of many heavy

elements (Ferland in Herstmonceux 1990). Stern and Shull (1990) have made the interesting suggestion that the ensemble of Oort clouds of comets belonging to all the stars in the galactic disk has locked up a supply of heavy elements roughly equal to that manifest in the interstellar medium. If that is the case, then the effective Z of the ISM is twice the value seen in large HII regions and is indeed significantly larger than solar.

Grains must surely all be vaporized and all molecules dissociated in the 10^{5-6} K coronal gas (though comets might persist). This gas gives rise to both X-ray emission lines and optical absorption ones of multiply ionized heavy elements. But apparently no one has ever seriously attempted to get abundances for it (Spitzer 1990).

The composition of the ISM varies systematically with location. You have to be clever to get the sign right, because the effect of metallicity on the surface temperatures of the ionizing OB stars makes the line ratio $[OIII/H\beta]$ go down when O/H goes up, as first understood by Aller (1942). Standing on his broad shoulders, a number of observers have found gradients in O/H, N/H, S/H and Ne/H (Shields 1990 and references therein), with higher metal abundances toward the galactic center and smaller outside the solar circle, by a factor of two or so. Ar, Ne, and probably S vary together with O. N is arguably underdeficient at low O/H and overenhanced at high O/H as befits a nominally secondary product (Peimbert et al. 1978).

The interstellar medium provides two interesting isotope ratios. First, C^{12}/C^{13} can be extracted from ratios in CH, CO, and other molecules. One has to worry about mass-dependent chemical fractionation and about saturated lines, the latter being alleviated by using, e.g., CO^{18} (Langer and Penzias 1990). The solar ratio is $C^{12}/C^{13} = 90$. The ISM value (Crane et al. 1990; Langer and Penzias 1990) rises from 24 near the galactic center through 30 at 5 kpc and 60 here to about 70 at 12 kpc (where O/H is definitely less than solar). This is just about the only evidence we have that interstellar gas has continued to evolve chemically since the solar system formed.

Second, D/H can be measured from the isotopically shifted component of Lyman alpha absorption. The received value (Boesgaard and Steigman 1985) is $D/H = 0.8-2 \times 10^{-5}$ from sight lines to half a dozen nearby stars. Murthy et al. (1990) have looked at some other stars and regard the data as setting various lower limits to deuterium abundance. They conclude that a consistent interpretation is $D/H = 4 \times 10^{-5}$ everywhere (including, in that case, the solar system). Because deuterium is so easily destroyed in stars, whatever value you vote for here is very much a lower limit to the primordial (big bang) abundance that would show up in unprocessed gas. Measured values of D/H well away from the solar neighborhood would be most valuable but are not likely in the near future.

The cosmic rays we see have had their elemental and isotopic abundances considerably modified by collisions with stationary ISM atoms. Given enough measured cross-sections for nuclear spallation reactions, experts can work backwards from the observed abundances to what must have been accelerated (Viola et al. 1988; Silberberg et al. 1990). Some selectivity in the initial acceleration pro-

cess is likely and suggested by the composition of solar flare particles (Breneman and Stone 1985). Very crudely, the accelerated particles are deficient in hydrogen and helium and enriched in some or most heavy elements, if you normalize around about carbon. A pattern of dependence on first ionization potential can be discerned (Waddington 1988).

All reasonable allowances having been made, the source composition still does not look quite solar (Waddington 1988) in the best-studied regime of intermediate energies (10^{7-10} eV amu⁻¹). The deviations are arguably larger at very high and very low energy. Highest energy component = normal, pure protons, and nearly pure iron have all been proposed.

Even within the intermediate energy range where the source composition is best defined, there is little agreement on how to account for it. Silberberg et al. (1990) suggest that supernova shock acceleration of pre-explosion stellar wind material (enriched in products of CNO cycling etc.) provides a good fit. Yanagida et al. (1990) have tried combining various proportions of SNI ejecta, SNII ejecta, and normal ISM to minimize (in the sum of the squares of the logs) deviations from source composition. They arrive at a best-fit ratio of SNI : SNII : ISM = 1 : 6–9 : 10–20, where the error bars are dominated by the differences between a couple of models for each supernova type. Meyer (1988a) favors a source composition drawn from the coronae of F-M stars with a small admixture of Wolf–Rayet material.

At the moment, the question that the source abundances are failing to answer is “where do the cosmic rays come from?” not “how do cosmic rays tell us about nucleosynthesis?” The exception is Li, Be, and B, which are enhanced over solar abundance by about 10^6 in the arriving intermediate energy cosmic rays. This is enough that the corresponding spallation of stationary ISM CNO atoms by cosmic ray protons and alphas will make all the Li⁶, Be⁹, and B^{10,11} we see over the age of the galaxy (Austin 1981; Arnaud 1986).

2.4. Other galaxies

2.4.1. Here and now

Individual stars in nearby galaxies reflect and confirm some of the things we believe from studies within the Milky Way. For instance, the Small and Large Magellanic Clouds have AGB stars with high lithium abundances whose winds are probably a principle source of lithium there (Smith and Lambert 1990). The most metal-deficient stars in the Clouds share with galactic ones the pattern $[O/Fe] > 0$ for $[Fe/H] < -1$ (Reiterman 1990), while sulphur tracks Fe (Spite and Spite 1990) and N is overdeficient, at least in the SMC (Dufton 1990). LMC planetary nebulae reproduce the enhancements of N and He, strongest for the most massive progenitors, found locally (Kaler and Jacoby 1990).

The average metallicity of the Clouds, based on a combination of stellar and ISM data, appears to be down from solar by a factor near three for the LMC and six for the SMC (Wheeler et al. 1989; Dufton 1990). Modelers of the evolution of the progenitor of SN 1987A would really like a slightly lower value (Nomoto et

al. in Woosley 1990), but star-to-star variations there may be enough to account for the difference. Metallicity has not increased smoothly with time (Richtler 1989).

Galaxies with very low gaseous metal abundance are of interest because the regression of $\Delta Y/\Delta Z$ is the best way we have to work back to the primordial (big bang) helium abundance (Pagel 1990). The long-standing record holder is I Zw 18 at $[O/H] = -1.6$ (Cambell 1990). No helium abundance has yet been reported for SBS 0335-052, which may break the record at $[O/H] = -2.0$ (Izotov 1990). Even without it and with some scatter in plots of known Z vs. Y for metal-deficient galaxies, it seems impossible to avoid concluding that primordial $Y = 0.23 \pm 0.01$ (Pagel 1990 and in Herstmonceux 1990).

Abundance gradients in the gas (and stellar) abundances of normal spirals are common (Shields 1990). The variation in slopes is probably real (van der Kruit 1990), and the range is from a couple of times solar at the centers of large spirals down to a fifth solar at the outskirts of small ones (Shields 1990). The metal-rich stellar population at the center of the Milky Way is echoed in M31 with central $[M/H] = +0.6$ and even M32, with central $[M/H] = +0.3$ (Schmidt et al. 1989).

Elliptical galaxies cover a wider range of both masses and compositions. The giant ones have very strong metal lines, but very weak gradients (Baum and Thomsen 1988; Baum 1990; Gorgas and Efstathiou 1987). The field star Mg/H drops only a factor of two over a factor of 10 in radius (Couture and Hardy 1990), while the globular clusters of M87 display no gradient at all (Couture et al. 1990). The average value over the whole volumes of a range of large ellipticals scatters widely around $[Fe/H] = 0$, and galaxy means are not as much correlated with luminosity as trends in spirals and dwarfs would have led one to expect (Gorgas et al. 1990). De Carvalho and Djorgovski (1990) have interpreted similar data to mean that metallicity is determined by two properties of elliptical galaxies, corresponding roughly to total mass (luminosity) and to luminosity density.

At the other end of the elliptical range, the dwarf spheroidals and dwarf ellipticals orbiting the Milky Way and Andromeda are all metal poor, down to $[Fe/H] = -1.9$ for Draco and Leo II (van der Kruit 1990; Hodge 1989; Zinn 1978). None is quite so metal poor as the most extreme globular clusters.

2.4.2. Long ago and far away

Our basic prejudice that the universe started with $Z = 0$ and that enrichment has occurred monotonically but non-uniformly is not seriously challenged by any of the existing data. A considerable expansion of information has taken place in this area since 1975 when all that could be said was that quasars (meaning the emission line regions) seemed to have essentially normal abundances. This remains true, a few perhaps even being iron rich (Collin-Souffrin 1986; Wills 1986). The broad absorption lines (thought to be produced in the quasars themselves) have at least solar metallicity, and perhaps twice it (Kwan 1990). We are presumably confirming with these data that enrichment occurs very quickly near the centers of very large galaxies. The emission line regions of distant radio

galaxies display the customary lines of O, Ne and C, but no serious abundance analyses seem to have yet been carried out (van Breugel and Mc Carthy 1990; Pedaly et al. 1990).

Quasar absorption lines produced by intervening gas, in contrast, reveal distinct underabundances. Ni, Cr, and Zn in the damped Lyman alpha systems (attributed to spiral disks along the line of sight) range from 0.04 to 0.25 solar with no strong redshift correlation (Meyer and Roth 1990). The Lyman limit systems, produced by slightly less dense gas, have $[M/H] = -1.5$ to -3.0 with C, O and Si in roughly solar ratios (Steidel 1990; Sargent et al. 1990). For the metallic absorption line systems, there is some correlation with redshift (Steidel 1990a), implying an increase in average Z in the absorbing gas of a factor of three between redshifts 3 and 1.5. The galaxies doing the absorbing have customary gradients, the equivalent width of MgII being correlated with impact parameter (Lanzell and Bower 1990) where the galaxy can be seen (these are necessarily at rather small redshift).

Relatively recent chemical evolution is indicated by the large galaxies in A370 ($z = 0.37$), which have lower values of Fe/H than contemporary galaxies of the same luminosities (Jablonka et al. 1990). Extremely metal poor gas is seen between the galaxies in rich clusters. The presence of an iron emission line in the spectra of X-ray emitting clusters has been thought to indicate Fe/H of about 1/3 solar. But the iron is apparently closely confined to the cluster core, at least in Perseus, so that the average Fe/H is much lower (Ponman et al. 1990).

3. Processes and sites

3.1. Conceptual changes since 1957

The array of processes and sites (Table 1) outlined by B²FH and Cameron (1957) has stood the test of time remarkably well. About three major augmentations and a handful of minor ones have been accommodated within the basic fabric without rendering it asunder, though some more extreme restructuring may just possibly be in sight.

First the early, hot dense universe has firmly established its place in the panoply of nucleosynthesis sites as essential for making all the elements up to helium. Advocates of a highly inhomogeneous early universe believe that it may contribute small amounts of many other elements.

Second of the major advances is the explicit treatment of explosive nucleosynthesis, meaning networks of reactions that do not come into equilibrium because the star is changing its structure faster than the reaction time scales. B²FH and Cameron (1957) allowed for relatively minor contributions from supernova explosions as the sites of the r- and p-processes and perhaps some rapid, high temperature hydrogen and helium burning. The industry really got started in the early 70's (Arnett and Schramm 1973), using the passage of a shock through the outer layers of an evolved, massive star to fine-tune abundances from those left by hydrostatic burning into better agreement with cosmic abundances.

A shock with sufficient energy to eject the envelope at the right speed is simply dumped at the bottom of the envelope. This aspect of the calculation remains ad hoc, because we do not yet understand exactly how 10^{51} ergs of the 10^{53} ergs available from neutron star formation is actually transferred to the envelope (Piran et al. 1990; Petschek 1990; Woosley 1990). But the most recent calculations for SN 1987A are beginning to use the same complete reaction network at all evolutionary phases, allowing out-of-equilibrium abundances to develop when and where they will, and so partially erasing the distinction between hydrostatic and explosive nucleosynthesis (Woosley et al. 1988; Nomoto et al. 1990). Non-equilibrium reactions are also present and treated with rapidly increasing accuracy in calculations of nova explosions and in Type I supernovae, where we believe that half or more of a solar mass of carbon and oxygen is incinerated to iron peak elements in minutes. The contributions of the several kinds of Type I supernovae to galactic chemical evolution have been considerably clarified in recent years. In particular, they have replaced core collapse supernovae of very massive stars as the most likely source of iron peak elements.

A third major change seems to be on the horizon. As more nuclides are included in reaction networks at each stage (30–300 is typical for heavy element burning) the distinctions among carbon, neon, oxygen, silicon, and nuclear statistical equilibrium burning inevitably become blurred. I would guess that a vintage 2005 review of these matters might once again discuss what we now call hydrostatic and explosive burning of about four different fuels as a collective “heavy element reactions in massive stars”.

Blake and Schramm (1976; Blake et al. 1981) had earlier explored a blurring between the s- and r-processes, called the n-process, in which the neutron capture and beta decay time scales were comparable. There may be observational evidence for something of the sort (Cameron 1988).

Another noteworthy expansion of the repertoire is the admission of neutrino-induced nucleosynthesis to the list of respectable processes. More than half the energy liberated by core collapse in Type II supernovae undoubtedly comes off as neutrinos and antineutrinos of the three known families. Domogatsky and Nadyozhin (1977, 1978) initially proposed that inverse beta decays, induced by electron neutrinos and sometimes followed by emission of a neutron or proton, could produce appreciable amounts of the bypassed (p-process) nuclides from adjacent, more abundant species. Woosley (1977) added to these charged current interactions the neutral current ones, in which a neutrino could inelastically scatter and excite a nuclide into a state from which it decayed by neutron emission. He concluded, however, that even the sum of the processes was too small to be the dominant source of any nuclide. The main Domogatsky and Nadyozhin (1978) paper circulated in preprint form in 1976 but was delayed in publication, which is how the correction came to be published before portions of the original idea.

The Mark III neutrino process (Woosley et al. 1990 and references therein) includes inelastic scattering and excitation by the higher-energy mu and tau neutrinos as well as electron ones and emission of protons and alpha particles as well as neutrons. The authors believe that the process is likely to be the major

contributor of Li^7 , B^{11} , F^{19} , La^{138} , and Ta^{180} and that it may be important for stable B^{10} , unstable Na^{22} and Al^{26} (though there is competition to make these elsewhere) and rare odd isotopes of Cl, K, Sc, Ti, V, Mn, Co, and Cu.

Recognition that Ne^{20} does not have a low-lying state with suitable spin and parity to complete the reaction $\text{O}^{16}(\alpha, \gamma)\text{Ne}^{20}$ broke the original alpha process into separate stages of carbon, neon, oxygen, and silicon burning without greatly changing either the temperatures and densities required to step through from the end of helium burning to the onset of nuclear statistical equilibrium or the final mix of products. The continuing biennial oscillations in the cross section for $\text{C}^{12}(\alpha, \gamma)\text{O}^{16}$, on the other hand, do not disturb the sequence of processes, but do make a considerable difference to the relative amounts of C (hence Ne later) vs. O available when they do burn and, therefore, to the final output (Fowler 1985; Caughlan and Fowler 1988; Rolfs and Rodney 1989, Sect. 7.2.2; Filippone et al. 1989).

3.2. *The early universe*

Big bang (cosmological) nucleosynthesis is alive and well (Krauss and Romanelli 1990). In fact, it probably has been ever since Hayashi (1950) got roughly the right neutron-to-proton ratio for a universe expanding and cooling somewhat faster than the neutron half life. The standard model assumes a completely homogeneous, isotropically expanding universe with lepton number equal to baryon number. Baryon number is the most important free parameter in the models, and results are usually quoted as limits on the present ratio of baryons to photons, η_b , or 10^{10} times this, η_{10} . The fraction of the closure density in baryons is then

$$\Omega_b = 0.0036 h^{-2} (T/2.74)^3 \eta_{10}$$

where h is Hubble's constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and T is the current temperature of the microwave background.

Qualitatively, the way to think of the situation is that, if there are lots of baryons, they find each other easily, so you get lots of helium produced and rather little deuterium left, and conversely for low baryon density. Items that have more or less been sorted out in recent years, leading to a definitive answer within the standard model are:

1. The neutron half life at $624 \pm 6 \text{ s}$ (Krauss and Romanelli 1990) is now responsible for uncertainties of only about 10%, comparable with the effects of error bars on the measured nuclear cross sections.

2. The number of neutrino species present at the MeV temperatures appropriate to cosmological nucleosynthesis is now almost certainly pinned down to three from the width of the Z^0 measured at CERN (Aleph 1989; Delphi 1989; L3 1989; Opal 1989). The point is that the more different kinds of things a Z^0 can decay into, the faster it will decay and so, given $\Delta E \Delta t = \hbar$, the wider an energy state it will be.

3. Though deuterium and He^3 abundances separately are quite difficult to get hold of, their sum can perhaps be determined rather well from solar wind data (Yang et al. 1984). Neither currently sets the tightest limit on Ω_b .

4. The use of regressions of $\Delta Y/\Delta Z$ for Population II stars and dwarf irregular galaxies of low metallicity has led to a rather convincing value of the primordial helium abundance (Pagel 1990; Steigman et al. 1989) of 0.23 ± 0.01 . This currently puts a firm lid on the cosmic baryon density at $\eta_b = 5 \times 10^{-10}$. Strong evidence that the correct value is 0.23 or lower would come very close to sending us back to the drawing board (Pagel 1990; Krauss and Romanelli 1990).

5. Much activity has been devoted to lithium. Li^7 is produced in two different reactions, $\text{H}^3(\alpha, \gamma)\text{Li}^7$ and $\text{He}^3(\alpha, \gamma)\text{Be}^7$ followed by a beta decay, at low and high density respectively. Thus least of it is produced at intermediate baryon density, $\eta_b = 1\text{--}5 \times 10^{-10}$. The value observed in warm but unevolved Pop II stars is in this range (Sect. 2.2.1) and, if this represents the primordial supply, we have clearly learned something.

Given the standard model and points 1–5, the baryon to photon ratio is trapped between 1.2 and 5.0×10^{-10} . That is, $\Omega_b = 0.004\text{--}0.018 h^{-2}(T/2.74)^3$. This may or may not be difficult to live with, depending on your beliefs about Hubble's constant, total Ω , and the nature of dark matter. The known luminosity density of the universe, if $M/L = 1$ as for a population of stars and gas, would contribute only 0.001–0.002 to Ω ; thus any value of H of order 100 or less seemingly commits us to the existence of at least some baryonic dark matter (brown dwarfs or whatever). From the other side, if you believe that galaxies and clusters are bound entities with $M/L \approx 100$ in solar units, even the upper limit on Ω pretty well forces us to accept some non-baryonic dark matter. If you wish to close the universe, then 99% of it is made of something very unlike ourselves.

We can weasel out of this in a couple of ways. Recent codes for calculating cosmological nucleosynthesis (Yang et al. 1984; Krauss and Romanelli 1990 and references therein) have not included the possibility of lepton number greatly in excess of baryon number. As Fowler pointed out some years ago (Fowler 1971), a dense sea of neutrinos or antineutrinos during cosmological nucleosynthesis forces the n/p ratio far from its thermodynamic value of $\approx 1/8$ and so can inhibit formation of helium (hence presumably lithium). It would be very interesting to see a state-of-the-art version of this calculation.

Instead, Fowler has come firmly out in support of one of the other escape routes, inhomogeneous nucleosynthesis. The idea is that the phase transition from a quark–gluon soup to hadrons could have left the universe with very large variations in density from place to place. Because neutrons can leak across magnetic field lines and protons cannot, this gives rise to regions of high and low n/p ratio. These undergo nucleosynthesis with relatively little leakage between zones, and what we see now results from a mixture of the products. Many calculations predicated on these assumptions and of varying degrees of accuracy now grace the literature (Applegate and Hogan 1985; Applegate et al. 1987, 1988; Kajino et al. 1990; Terasawa and Sato 1990; Kajino and Boyd 1990; Alcock et al. 1990; Reeves et al. 1990; Kurki-Suonio et al. 1990). The points on which they agree and disagree can be summarized as follows:

1. Inhomogeneous nucleosynthesis increases somewhat the upper limit on Ω_b . But whether you can push Ω_b nearly to unity (Mathews et al. 1990) or only to 0.2–0.3 (Reeves et al. 1990; Kurki-Suonio et al. 1990) is disputed.

2. If the process is important, the early universe will contribute not only H, He, and Li⁷, but also Be⁹, CNO with non-solar isotope ratios, and even a bit of r-process material (Kawano et al. 1990; Terasawa and Sato 1990). The disagreement arises over whether the amounts are likely (the Kellogg group) or unlikely (Terasawa and Sato 1990) to be detectable. There is no observational evidence at the moment for such a component (Pagel 1990).

3. Lithium is important, because even in the most favorable calculations, pushing Ω_b up near 1.0 also raises primordial Li/H to or beyond 10^{-9} , close to the value seen in unevolved and unmixed Population I stars. If the real primordial abundance is the level found in 5500–6500 K unevolved Population II stars, $\text{Li}/\text{H} = 1\text{--}2 \times 10^{-10}$, then the deal is off. But all will be well if stars can destroy lithium in the pattern needed (a) to get the interstellar value down to $1\text{--}4 \times 10^{-10}$ as seen (Sect. 2.4) in the Milky Way and the LMC (Sect. 2.5.1) and (b) to lower the surface abundances in warm Pop II stars to a uniform 10% of what they started with (Alcock et al. 1990; Mathews et al. 1990). The treatment of lithium destruction by the experienced stellar evolution group at Yale (Deliyannis et al. 1989; Deliyannis et al. 1990) indicates that the necessary destruction will not occur unless meridional circulation or some other non-standard (and currently non-calculable) form of mixing is invoked to take surface lithium down to where it will be burned through to helium. These considerations are currently the firmest objection to inhomogeneous nucleosynthesis as a way around the limit on baryon density. I find it slightly unsatisfactory that anything as scarce and unromantic as lithium should be so important.

3.3. *Hydrogen and helium burning*

The most ancient and honorable of the problems in this sector is the persistent deficit of solar neutrinos. Mercifully, it seems not to be our problem. For a good many years (Trimble and Reines 1973; Bahcall 1989), the chemists and physicists told the astronomers that our solar models were no good, and the astronomers and the chemists told the physicists that their cross-sections were no good, and the physicists and the astronomers told the chemists that their argon recovery techniques were no good.

But the physicists have now laid claim to the problem and proposed two solutions. First, neutrinos may have large enough magnetic moments and the sun a strong enough internal field for the electron neutrinos produced by hydrogen burning to be rotated into mu and/or tau neutrinos (Okun 1986; Voloshin and Vysotskii 1986). Second, the rest masses and other properties of the three families may be such that neutrino oscillation as catalyzed by the presence of nuclei turns many of the ν_e into ν_μ (Mikhayev and Smirnov 1986; Wolfenstein 1978). The latter is called the MSW effect after the initials of its discoverers and has been endorsed by Bethe (1989) who unquestionably hold the record for length of time spent thinking about hydrogen burning (Bethe 1939). This kind of oscillation can

reduce the flux of ν_e to well below one-third of that coming out of the nuclear reactions, because once the particles leave the sun, there are no nuclei around to catalyze the reverse process.

A third solution, in which the same weakly interacting massive particles (WIMPs) both close the universe and smooth out the solar central temperature gradient is not quite ruled out (Caldwell et al. 1990) but perhaps does not sound quite so attractive as when it was first proposed (Faulkner et al. 1986 and references therein).

Each of the other two solutions also buys you something else. The magnetic effect arguably enables us to understand correlations of the neutrino flux as measured by Davis at the Homestake Mine with another magnetic phenomenon, the sunspot cycle (Bieber et al. 1990) and perhaps with changes in the frequencies of solar p-mode oscillations (Krauss 1990). MSW, on the other hand and with a good deal of additional physics folded in, tells you the relative masses of the three neutrino species, with the ν_τ turning out at 15–20 eV, within striking distance of closing the universe as hot dark matter. In addition, the relative fluxes reported by the Homestake experiment (1/4–1/3 of the standard model prediction), by the Kamioka detector (1/2 of standard prediction), and by the Soviet-American Gallium Experiment (zero, but with large error bars) can be interpreted as the effect of energy dependence of the neutrino oscillations. I apologize for the fact that the same word is customarily used for neutrino transmogrification and for solar shivers.

Neither mechanism quite accounts for all details of all observations, and some help from astrophysics or nuclear physics may still be needed. But it now seems a good deal less likely than it did five years ago that we will end up with reinterpretations of hydrogen burning and main sequence stars drastic enough to affect the grand scheme of nucleosynthesis.

At this point, then, we can say with somewhat renewed confidence that most stars get their energy from fusion of hydrogen to helium for most of their lives. The dominant nucleosynthetic effects will be (a) destruction of Li, Be, B, H^2 , and He^3 in material that gets hotter than about 10^6 K at any stage (This varies somewhat among species; Li and H^2 are easier to destroy than Be and He^3). (b) production of He, much of which is later burned through to C and O and beyond, but enough remains as helium that, observationally and, increasingly, theoretically, $\Delta Y/\Delta Z \geq 2-3$ in stellar ejecta, and (c) production of N and rearrangement of CNO isotope ratios such that mixtures of material that has and has not been through a CNO hydrogen burning zone can account for most of the assorted ratios we see in stars and the interstellar medium.

Hydrogen burning at 10^8 K and above can penetrate from the CNO cycle into similar cycling among Ne–Na and Mg–Al, or these can be separately initiated from Ne and Mg already present. Sufficiently high temperatures may be reached hydrostatically in hydrogen-burning shells of evolved massive stars, but perhaps more often under explosive conditions in novae and Type II supernovae. In the latter case, only about one proton capture per heavy nucleus will have time to take place leading to isotope ratios far from equilibrium.

Reaction rates for hydrogen burning (and most of the other relevant reactions) under stellar conditions are periodically updated by the Kellogg group (e.g. Caughlan et al. 1985; Caughlan and Fowler 1988). Of the necessary cross-sections, the direct proton-proton one remains, uniquely, unmeasured. But it is adequately calculable from the half-life of the neutron (Rolfs and Rodney 1989, Sect. 6.1.1).

At the other end of the hydrogen-burning temperature range, some of the reactions that lead out of CNO cycling and into and through Ne–Na and Mg–Al cycling do not yet have adequate laboratory data on cross-sections and energy levels. $O^{17}(p,\gamma)F^{18}$ and $Al^{26}(p,\gamma)Si^{27}$ are examples. The result is some uncertainty about when and where the cycles can operate and so about whether they will really produce $Ne^{21,22}$, Al^{26} , and so forth (Rolfs and Rodney 1989, Sect. 6.2.3 and 6.3). Many of the nuclides involved can also be made by captures of single n's or p's in s, r, and explosive hydrogen zones.

Al^{26} is the only one of these currently constituting a hot topic. Production mechanisms and sites under study include $Mg^{25}(p,\gamma)$ in AGB stars (Frantsman 1990), Wolf-Rayet stars and supernovae coming from them (Signore and Dupraz 1990), and novae (Higdon and Fowler 1990; Weiss and Truran 1990), and the neutrino process (Sect. 3.1) in Type II supernovae (Woosley et al. 1990).

Helium burning has a difficult time getting started because Mother Nature neglected to arrange for any stable nuclei with $Z = 8$. It would be fun to run some models of stellar evolution and nucleosynthesis with an artificially stable Be^8 or Li^8 and see what happens. In the real world, gas must get hot enough and dense enough to build up a small equilibrium concentration of Be^8 to the point where beryllium nuclei begin to catch an additional α particle to make stable C^{12} . This is expected to happen at a temperature near 10^8 K and a density from $10^{2.5}$ to 10^{6-7} $g\ cm^{-3}$ (higher densities being needed in lower mass stars). Helium burning thus occurs in all stars more massive than about $0.5 M_{\odot}$. This includes everybody with a hydrogen-burning lifetime less than the age of the universe. Helium white dwarfs are, however, found among the cataclysmic variables, where mass loss has stripped the envelope from a more massive star after hydrogen burning was fairly complete but before helium burning set in. Ignition is explosive in wholly or partially degenerate helium ($\rho \gtrsim 10^5$) in a way that (a) is presumed responsible for the readjustment of low mass stellar structure from red giant to horizontal branch type and (b) may cause some additional mixing above and beyond the three standard dredge-ups.

Other important reactions occur in helium-burning zones. C^{13} and N^{14} left from CNO cycle hydrogen burning will be processed via $C^{13}(\alpha, n)O^{16}$ and $N^{14}(\alpha, \gamma)F^{18}(\beta)O^{18}(\alpha, \gamma)Ne^{22}(\alpha, n)Mg^{25}$. If these neutron sources are to fuel the s-process (Sect. 3.5.2) then the neutrons must not all get captured by C^{12} , Mg^{25} and other irrelevant nuclides and the supplies of C^{13} and N^{14} must be replenished to get enough neutrons per iron seed to reach, e.g., Pb and Bi. This implies complicated, but expected, contact between the hydrogen and helium burning zones (Iben and Renzini 1983).

Explosive helium burning is likely to happen only in supernovae of various sorts. Its role in the r-process is addressed later (Sect. 3.5).

The largest residual uncertainty in helium burning is the cross section for $C^{12}(\alpha, \gamma)O^{16}$ already mentioned. Some modellers have dealt with the problem by carrying out parallel series of calculations with a high and a low rate. The amount of oxygen ejected by a supernova can differ by nearly an order of magnitude between the two (Woosley et al. 1988). The detection of 1–3 M_{\odot} of fresh oxygen in the ejecta of SN 1987A has led, for instance, Thielemann et al. (1990) to conclude that a high reaction rate must be right.

Helium burning terminates because the excited state of Ne^{20} lying just above the threshold for $O^{16}(\alpha, \gamma)Ne^{20}$ is, anomalously, a 2^- state which cannot be formed from two 0^+ nuclei like O^{16} and He^4 (Rolfs and Rodney 1989, Sect. 7.3).

3.4. Heavy element burning

Heavy element burning occurs in all stars that get hot enough to ignite carbon ($\gtrsim 10^9$ K) before accelerating mass loss strips them down close to the hydrogen-burning shell or the core becomes so degenerate that it cannot contract and heat any further, thereby shutting off nucleosynthesis. I have never been able to decide whether it is (a) obvious, (b) an uninteresting coincidence, (c) a curious and interesting coincidence, or (d) a fundamental fact demanding explanation that the mass cut between burn and not burn comes so close to that between stars that leave white dwarfs and stars that go on to supernovae. The cuts are not quite identical, in that binary systems provide evidence for a few O–Ne–Mg white dwarfs left from cores of stars that burned carbon non-explosively before shedding their outer layers. But the two dividing lines come close enough that explaining the distinction to beginning students is tricky. There may also be a narrow intermediate mass range that ignites carbon explosively and does not live to tell the tale. If stars in this class are responsible for some subset of Type I supernovae, then they must have lost all their hydrogen before terminal carbon ignition.

Table 4. The seven ages of a 20 M_{\odot} star

Fuel	Central Density $g\ cm^{-3}$	Central Temperature K	Photon Luminosity $erg\ sec^{-1}$	Neutrino Luminosity $erg\ sec^{-1}$	Duration yr
H	5.6	4.0×10^7	2.7×10^{38}	—	1.0×10^7
He	940	1.9×10^8	5.3×10^{38}	small	9.5×10^5
C	2.7×10^5	8.1×10^8	4.3×10^{38}	7.4×10^{39}	300
Ne	4.0×10^6	1.7×10^9	4.4×10^{38}	1.2×10^{43}	0.38
O	6.0×10^6	2.1×10^9	4.4×10^{38}	7.4×10^{43}	0.50
Si	4.9×10^7	3.7×10^9	4.4×10^{38}	3.1×10^{45}	2 days
Grav. Potn.	10^9 – 10^{15}	4×10^{10}	10^{42} – 10^{44}	10^{52}	10 seconds

Table 4 (from Arnett et al. 1989; similar ones appear elsewhere) shows the central temperature and density and time scales of the seven major nuclear burning stages in the life of a 20 M_{\odot} star, corresponding to the seven ages of man. I am not aware of any fundamental changes in the treatment of heavy element

burning in recent years. Both laboratory and theoretical values of nuclear energy levels and cross sections have continued to improve.

The most important advances seem to be (a) the inclusion of very many more nuclides in recent reaction networks and (b) the concomitant capability of keeping track of non-equilibrium abundances when convection or other changes in the star modify the environment of a nucleus faster than it can react (Thielemann and Arnett 1985). The basic outcome remains as it was:

- Carbon burning makes Ne^{20} (mostly), Na^{23} , and Mg^{24}
- Neon burning makes Mg^{24} and Si^{28}
- Oxygen burning makes Si^{28} and S^{32}
- Silicon burning makes iron peak elements

plus, in all cases, smaller amounts of adjacent nuclei produced by capture and expulsion of stray neutrons, protons, and alpha particles. And the theorist's presupernova star still looks a lot like an onion (Trimble 1982, Fig. 3). The production of only even- Z elements by the dominant reactions, leaving the odd Z 's to act a bit like secondary nuclides, continues to be associated with the odd/even effect (over-deficiency of, e.g., Na and Al relative to their neighbors) in metal-poor stars. (Molaro and Bonifacio 1990)

The minor products get thoroughly reassorted during outward passage of the supernova shock. The final product mix depends on shock energy, which is currently an ad hoc variable parameter. But it is also strongly affected by the n/p ratio (neutron excess) left behind by hydrostatic processes. A lower limit to this neutron excess comes from the CNO cycle, which leaves much of a Population I star's initial complement of CNO as N^{14} , which helium burning largely processes to Ne^{22} . Thus even when most of the core of a star is C^{12} , O^{16} , and Ne^{20} , it will still have at least one excess neutron for every 10^4 baryons. This number rises through the later burning stages up to the iron core which collapses. At this stage, the parameter is generally given as Y_e , the number of electrons per baryon. Central values are $Y_e = 0.41\text{--}0.45$, lower in the cores of less massive stars where high densities and low temperatures encourage direct electron captures on some nuclei (Thielemann and Arnett 1985; Hillebrandt and Wolff 1985). Y_e at the center makes some difference to how likely a shock is to survive and make a Type II explosion happen (Hillebrandt and Wolff 1985). Y_e in the ejecta determines whether you get the right ratios of isotopes like $\text{Fe}^{54,57,58}$ to Fe^{56} . It is never smaller than 0.49 in the material ejected from the 1987A models computed by Thielemann et al. (1990) and Nomoto et al. (1990). Not surprisingly, these models yielded solar ratios of Fe^{54} and Fe^{57} to Fe^{56} (and the ratio of Fe^{57} to Fe^{56} implied by infrared lines from the ejecta, Varani et al. 1990), but greatly underproduced Fe^{58} .

3.5. *The p-, s-, r-, and x-processes*

The first step in understanding these is to sort out which of the nuclides beyond $A = 62\text{--}70$ is made by each. Table 3 of Anders and Grevasse (1989) does such a fine job of this (omitting only neutrino-induced nucleosynthesis) that I am

constrained to plagiarism, invention, or silence, and will opt mostly for the third. Once the nuclides and their abundances have been determined, then each process must be persuaded to yield both the right total amount of its products and the right ratios among them.

Total amount, in general, depends upon the quantity of seed nuclei exposed to the process, and the ratios upon the intensity of the exposure. For instance, lots of iron peak nuclei bathed in a handful of neutrons each will give you lots of $A \approx 70$ nuclides, but a few seeds must capture more than 150 neutrons each to reach the actinide region. The distribution of exposures is frequently assumed to be exponential to account for the overall steep decline of abundances from the iron peak onward to the actinides.

The observed abundance patterns must then be fit by the convolution of this exposure distribution with the capture (etc.) cross-sections of the nuclides concerned. Structure in cross-section vs. A is dominated by the increased stability (hence lower capture cross sections) at the closed nucleon shells or magic numbers $Z = 50, 82$ and $N = 50, 82, 126$. The general plan of attack has been quite successful.

3.5.1. The p-process

Identifying the products of the p-process is easy. They are the ones that cannot be reached any other way (Table 5). They have the fewest neutrons of the stable isotopes of each element, and all are even A . The total mass in p-nuclides is 1–2% of that in the r- and s-nuclides (Table 2) that are believed to be their immediate predecessors. Thus only a small fraction of the more neutron-rich nuclides needs to undergo proton captures or (γ, n) reactions at a temperature of $1\text{--}3 \times 10^9$ K to account for what we see. It is, therefore, quite difficult to invent a process so rare that it cannot account for the p-nuclides. I should like, however, to propose collisions of comets in mildly relativistic orbits around neutron stars as a candidate. A plot of p-process abundances using current best data (Anders and Grevasse 1989) is indistinguishable from Fig. 3 of Trimble (1975). Only two values of A have more than one p-process nuclide. In each case, one (La^{138} , Ta^{180}) is scarce even by standards of the process. This must mean something, but I am not sure what. Looking at Table 5, one would guess that W^{180} would be harder to form than Ta^{180} , but it clearly is not so.

Cameron (1957) tentatively placed his production of excluded nuclei in hydrogen-rich regions of Type II supernovae. It now seems more likely (Woosley and Howard 1990; Rayet et al. 1990) that the necessary conditions will be achieved as a supernova shock passes out through what was the oxygen-burning layer of the progenitor star. Thus the dominant reactions must be photodisintegrations rather than proton captures, though (γ, p) followed by (p, n) or (p, γ) makes some contribution.

Because we have no extra-solar system data on p-nuclides and because their production depends on fine details of the production site, it is impossible to say enough about the time evolution of p-processing to be able to use unstable nuclides from it as cosmochronometers (Cowan et al. 1991). One would expect

extreme over-deficiencies of p-products in metal-poor sites since their r- and s-process ancestry means that they are secondary or even tertiary products of nucleosynthesis.

Table 5. Products of the s, r, and p processes between Yb and Hg ($Z = 70-80$)

Proton Number	104	105	Neutron Number					
			106	107	108	109	110	111
80								
79								
78								
77								
76				Os184			<u>Os186</u>	<u>Os187</u>
75							<u>Re185</u>	
74			W180		<u>W182</u>	<u>W183</u>	<u>W184</u>	
73				Ta180	<u>Ta181</u>	Ta182		
72	<u>Hf176</u>	<u>Hf177</u>	<u>Hf178</u>	<u>Hf179</u>	<u>Hf180</u>	Hf181		
71	<u>Lu175</u>	<u>Lu176</u>	Lu177					
70	<u>Yb174</u>		<u>Yb176</u>					

Table 5. (Cont.)

Proton Number	112	113	114	Neutron number				
			115	116	117	118	119	120
80				Hg196		<u>Hg198</u>	<u>Hg199</u>	<u>Hg200</u>
79						<u>Au197</u>		
78	Pt190		<u>Pt192</u>	<u>Pt194</u>	<u>Pt195</u>	<u>Pt196</u>		
77			<u>Tr191</u>	<u>Ir193</u>				
76	<u>Os188</u>	<u>Os189</u>	<u>Os190</u>	<u>Os192</u>				
75	<u>Re187</u>							
74	<u>W186</u>							
73								
72								
71								
70								

3.5.2. The s-process

The entity called the s-process really does exist. Solar system abundances peak near the neutron magic numbers $N = 50, 82,$ and 126 ; the peaks show much more clearly when you plot nominal s-products separately (Trimble 1975, Fig. 3); and smooth away almost completely when you plot the product of abundance times capture cross section (Fig. 7 of Anders and Grevasse 1989). These cross sections are all relatively well known since only stable nuclides are involved. Evolved stars with excesses of the nominally s-dominated elements Sr, Y, Zr, Ba, and La, but not of adjacent nominally r-dominated elements, confirm the discreteness of the process. FG Sge, with the whole range of lanthanides (Wallerstein 1990) is

genuinely unusual but also, of course, a problem. Anomalous isotope ratios in Mg and Zr as measured from lines of MgH and ZrO are also a signature of the s-process at work in AGB stars (Malaney and Lambert 1988; Smith 1988).

The entity is not, however, monolithic. No single choice of neutron density, time scale, initial iron peak population, and other conditions gives rise to the full range of products. Recent studies (Käppeler et al. 1989) require at least two sites and sets of environmental parameters. Currently these are identified with (a) cores of massive stars ($\gtrsim 8 M_{\odot}$) near the end of core helium burning, with $\text{Ne}^{22}(\alpha, n)\text{Mg}^{25}$ (Cameron 1960) as the primary neutron source, to make $A \leq 90$ nuclides (Prantzos et al. 1990) and (b) convective, thermally pulsing shells of hydrogen and helium burning during the asymptotic giant branch phase of less massive stars, with $\text{C}^{13}(\alpha, n)\text{O}^{16}$ as the neutron source, to make much smaller amounts of $A \geq 90$ nuclides (Hollowell and Iben 1990).

The two regimes require about 3 and 15 neutrons per iron seed respectively, and the yield is not so simple a function of initial $[\text{Fe}/\text{H}]$ as you might have expected (Prantzos et al. 1990). Steady and pulsating neutron sources that have the same total number of neutrons passing each seed lead to very similar relative abundances (Käppeler et al. 1990).

The main difference between steady and pulsed neutron exposures (Beer 1988) occurs where the process must cross unstable nuclides like Ir^{192} in Table 5. It has a better chance of getting across the bridge if neutrons are continuously available, and the ratios of nuclides formed by the branch between early decay and another n capture provide hints of the time scales and exposure levels responsible for solar system abundances. A particularly rich array of these occurs in the Sm–Gd region (Beer 1988). The Karlsruhe group have been instrumental in producing nuclear properties near those branch points. To keep on top of the subject, watch for papers and preprints with H. Beer and/or F. Käppeler among the authors. The branches of the s-process always rejoin after one or two additional captures and decays.

Given that the identification of Tc in the spectra of a few red giants (Merrill 1952) counted as the first evidence for s-processing here and now, it comes as a shock that Lattanzio and Malaney (1989) should have proposed that the real source is decay and photodisintegration of actinides in the stellar atmospheres, rather than upward mixing of s-products.

3.5.3. The r-process

The r-process comes closest to what Gamow (1935, 1946) had in mind for cosmological nucleosynthesis – lots of neutrons around that are captured until nuclei choke (most notably at closed shells) and so must beta decay one to ten times before another capture is possible, followed by slower beta decays back to stable isobars. Most of the nuclei involved are highly unstable, and cross sections and energy levels must be calculated. Cowan et al. (1990) tabulate the best available values Ne^{20} right on up to 113^{337} (Cameronium?) and give a wealth of other information about the r-process, its products, and problems.

The separation of s- and r-components for the many nuclides made by both processes normally starts with the s ones, because of the more reliable cross sections. Using them and the abundances of the s-only products, you (or rather Burnett and Woolam 1990; Käppeler et al. 1989; and other experts) make use of the expected smoothness of $N_A\sigma_A$ to figure out how much of each mixed nuclide comes from the s-process and subtract it off. The r-only and r-residual abundances resulting fit on to the same smooth $N(A)$ curve (Käppeler et al. 1989). The remaining structure in plots of abundance times cross section then presumably reflects neutron exposure levels and time scales. The structure is not necessarily exactly what one might have expected (Burnett and Woolam 1990).

Unlike the case of the s-process, however, the r-nuclides in the solar system arguably come from a homogeneous set of environments. The narrowness of the peaks at $A = 130$ and 195 , reflecting beta decays from closed shells at $N = 82$ and 126 , suggests that all the contributing sites had much the same neutron fluxes and time scales (Mathews and Cowan 1990).

The hardest part of r-processing is reaching the actinides (Kratz 1988). Cameron (1957) had originally postulated a somewhat separate actinide r-process. And indeed some of the sites that might otherwise be OK fail in this respect (Wefel et al. 1981).

Proposed sites include novae, neutron stars colliding or falling apart or being swallowed by black holes, helium or carbon burning zones of massive stars during shock passage, helium-flashing stellar cores, and (as B²FH and Cameron 1957 first thought) cores of supernovae. References to these proposals are collected by Cowan et al. (1990, 1991) and Mathews and Cowan (1990). In 1975 I cautiously came out in favor of supernova cores on the grounds that they had more iron seed and more neutrons than any place else. The chief difficulty was, and is, getting the stuff out from close to the incipient neutron star without totally disrupting the desired abundance patterns. Whether bubbles and jets of material from deep inside supernovae deviating from spherical symmetry can solve this problem remains to be discovered from three-dimensional calculations hardly yet on the horizon (Cowan et al. 1990).

We are pretty sure (Thielemann et al. 1990) that SN 1987A did not eject any r-process material, because the gas close to the boundary between neutron star and ejecta was never exposed to high enough density ($\rho \gtrsim 10^{11-12} \text{ g cm}^{-3}$) to liberate the required 10-100 neutrons per seed nucleus. But its modellers believe that a somewhat less massive star, undergoing an explosion calculated with comparable care, would eject r-nuclides in useful amounts.

When neutron exposures and time scales are tuned to fit solar system abundances of stable nuclides, production of the customary cosmochronometers, U, Th, Re, and Os, becomes calculable. Discussions of the age of the galaxy and of chemical evolution that make use of these clocks are contingent on the r-process having been correctly understood (Cowan et al. 1990, 1991).

3.5.4. The x-process

The origin of subsets of these delicate nuclides is currently ascribed to:

- conventional hot big bang (H^2 , He^3 , 10% of Li^7)
- inhomogeneous hot big bang (H^2 , He^3 , 10% of Li , Be , B)
- cosmic ray spallation (some Li^7 , all of Li^6 , Be , B)
- winds of AGB stars (rest of Li^7)
- neutrino-induced supernova processes (all of Li^7 , B^{11} ; much of B^{10})

all of which are mentioned in previous sections. One gets the initial impression that, if these all operate, some things would be over-produced. The uncertainties in all processes (e.g. much of the cosmic ray spallation comes from lower energy particles than those directly detected at earth) are probably such that neither serious disagreement or complete confirmation can be claimed for any of them.

3.6. Supernovae

Table 6 shows the amounts of elements from carbon to copper produced by a Nomoto et al. (1984; Thielemann et al 1986) Type Ia supernova and a Woosley et al. (1988) Type II. The former ejected 1.32 solar masses of heavy elements, the latter (which is a $20 M_{\odot}$ star model for SN 1987A) $2.67 M_{\odot}$ of heavy elements. The Table may remind you of horse and rabbit stew (one horse to one rabbit), but until rather recently Sb–Sbc galaxies like ours were thought to have roughly equal rates of Type I and Type II events (Tammann 1982). On that assumption,

Table 6. Chemical composition of supernova ejecta

Element	SN Ia (Nomoto et al. 1984) M_{\odot}	SN II (Woosley et al. 1988) M_{\odot}
C	0.032	0.018
N	2.6×10^{-8}	0.012
O	0.14	1.6
F	3×10^{-11}	1.1×10^{-6}
Ne	0.012	0.18
Na	1.5×10^{-5}	0.014
Mg	0.023	0.1
Al	6.6×10^{-4}	7.8×10^{-3}
Si	0.165	0.11
P	1.7×10^{-4}	6×10^{-4}
S	0.1	0.053
Cl	1.5×10^{-4}	1.2×10^{-4}
Ar	0.022	0.011
K	7.9×10^{-5}	9.4×10^{-5}
Ca	0.042	0.0096
Sc	5.7×10^{-7}	1.1×10^{-6}
Ti	6.9×10^{-5}	3.3×10^{-4}
V	2.6×10^{-5}	1.2×10^{-5}
Cr	0.011	0.0022
Mn	8.0×10^{-3}	4.8×10^{-4}
Fe	0.67	0.14
Co	4.7×10^{-4}	2.8×10^{-4}
Ni	0.073	5.9×10^{-3}
Cu	4.4×10^{-7}	1.0×10^{-4}

the Type I's would clearly dominate not only iron production (this used to be taken as an argument against certain kinds of SN I models) but also Si, S, Ar, Ca, V, Cr, Mn, Co, and Ni. Opinion on the rates has changed, and SN II's are now supposed to outnumber SN I's by two or three to one (van den Bergh et al. 1987; van den Bergh 1990) even at the present time, and considerably more so in the past (Matteucci and Tornambe 1988).

With the odds 3:1 against them, the SNI's still win on Fe and contribute significantly to even- Z elements from Si to Cr (Wheeler and Harkness 1990). But oxygen most particularly is a Type II product.

3.6.1. Type I supernovae

Type I's will be taken to mean classical SNIa's (found in both old and young stellar populations, etc.) unless further qualified. The arguments for associating them with exploding carbon-oxygen white dwarfs or cores probably in binary systems, are retold in the works by Trimble (1982), Petschek (1990), Woosley (1990), and Piran et al. (1990), and a countably infinite number of other places.

The first step is to sort out the difference between detonation and deflagration. The rule is that detonations propagate as supersonic shocks and deflagrations subsonically.

As a result, a carbon detonation supernova burns essentially everything through to iron peak nuclei. This is good for getting a nice bright event (and making Hubble's constant small) but bad for matching SN I spectra, which display lines of O, Ne, Si, Ca etc. more prominently than those of Fe and Co. Deflagration, on the other hand, goes more slowly and runs out of steam, leaving one third or more of the outer part of the star unburned and partially burned. This results in the abundances shown in Table 6 and spectra much like observed ones (Wheeler and Harkness 1990). Everybody who has sent me a preprint on the subject over the last year or so agrees with this picture of SN Ia's and their contributions to nucleosynthesis.

Type Ib events do not currently promote similar good fellowship. Advertized progenitors include very massive stars evolving through a Wolf-Rayet phase, intermediate mass stars undergoing core collapse supernovae when their helium cores have reached $3-4 M_{\odot}$ (vs. about $6 M_{\odot}$ for 1987A), and accreting white dwarfs in which detonation occurs, but away from the center of the star. SNIc's (Wheeler and Harkness 1990) are even less well defined, but are thought to share with Ib's an association with relatively young stellar populations. The only nucleosynthetic models for either to have been worked out in any detail are the intermediate mass helium star ones (Nomoto and Shigeyama 1990; Shigeyama et al. 1990). Such models eject less oxygen and more Ni^{56} than did 1987A (Nomoto in Herstmonceux 1990), which reproduces the light curves reasonably well. The Ic's may simply be one extreme of the Ib range, for instance the lowest-mass helium cores (Nomoto et al. 1990a).

3.6.2. Type II supernovae

Supernova 1987A has done a great deal for nucleosynthesis and galactic evolution, most obviously by making both observers and theorists supernova conscious. As a result, nearly all events discovered in the triennium after 23 February 1987 received at least a type spectrogram. And several groups who had been modelling advanced evolution of massive stars for some years were encouraged to calculate very nearly the same star (or, at any rate, the same input parameters of composition and mass), allowing comparison of results.

It did something else that I only came to appreciate while writing this review. It persuaded modellers to report nucleosynthetic products in absolute units for comparison with observed values like the $0.075 M_{\odot}$ of Ni^{56} implied by the light curve and gamma ray lines (Arnett et al. 1988). Thus you can tell at a glance that the Thielemann et al. (1990) model ejected $1.48 M_{\odot}$ of O^{16} , $0.228 M_{\odot}$ of Ne^{20} , $0.147 M_{\odot}$ of Mg^{24} , and so forth from hydrogen to gallium. By the same token, the Woosley et al. (1988) model ejected $1.6 M_{\odot}$ of O^{16} , $0.18 M_{\odot}$ of Ne^{20} , $0.096 M_{\odot}$ of Mg^{24} , and so forth from hydrogen to zinc, when the cut between neutron star and expelled envelope was drawn to give the right amount of Ni^{56} . Both of these are high $\text{C}^{12}(\alpha, \gamma)\text{O}^{16}$ models of $20 M_{\odot}$ stars with $6 M_{\odot}$ helium cores at the time of collapse, and initial metallicity about $1/3$ solar.

Now try to extract the same information from slightly earlier models published by the same experienced people (e.g. Thielemann and Arnett 1985a; Woosley and Weaver 1981, 1982, 1987). These references tabulate or graph not masses or numbers of atoms, but “overproduction factors” (i.e. $[\text{X}^i/\text{H}]$ or $[\text{X}^i/\text{O}^{16}]$ or some other normalization, plus, if you are lucky, the total mass of heavy elements ejected. Since they used different solar abundances and other normalizations, comparison is difficult. At any rate, I failed to extract numbers that I trusted enough to add either to Table 2 or to Table 6. Thus the statements that follow are largely qualitative.

Nucleosynthesis by Type II supernovae has the following properties:

- The more massive the progenitor, the larger the He core it grows
- The larger the helium core, the more heavies ejected, proportionately as well as absolutely
- The ratio of iron peak elements to everything else depends primarily on the cut between the neutron star and the ejecta; 1987A has made clear that rather little iron etc. comes out
- Low initial metal abundance gives you somewhat more helium and a lot less of the odd elements and neutron rich isotopes from C to Fe; dominant products are much less affected
- The ratio of O and its burning products to C and Ne is a steep function of the $\text{C}^{12}(\alpha, \gamma)\text{O}^{16}$ rate; for instance, as the models by Woosley and Weaver (1981, 1982, 1987) evolved, $[\text{Ne}^{20}/\text{S}^{32}]$ went from $+1.0$ to -0.7
- Input shock energy determines the temperature of explosive burning, but T scales only as $E_0^{1/4}$, so it does not dominate differences among models.

Stars more massive than $100\text{--}150 M_{\odot}$ will experience core collapse initiated by electron-positron pair production, during or before oxygen burning. Their

contributions to nucleosynthesis now are small because such stars are rare, and even smaller if they collapse directly to black holes. If, however, some combination of rotation and explosive oxygen burning inhibits collapse, then much of the helium core will be processed to heavy elements. At the low end of the mass range, a $45 M_{\odot}$ He core (El Eid and Prantzos 1988) made more oxygen than anything else, but also Mg, Si, S, Ar, and Ca in roughly the proportions present in Cas A. Helium cores of $200\text{--}500 M_{\odot}$ (Stringfellow and Woosley 1998) burn nearly everything, yielding approximately equal amounts of O, Si, and Fe peak, with C, Ne, and Mg smaller by a factor near 10. Such objects and events could have been important to pregalactic nucleosynthesis or the very early history of the galaxy.

There does not currently exist in the literature a uniform series of nucleosynthesis calculations as a function of stellar mass, but keeping everything else fixed, from which one can easily collect the numbers needed to simulate galactic chemical evolution, in the way that Arnett's models provided the raw material for Table X of Trimble (1975). We can perhaps hope for something of the sort in a few years, when the lessons of 1987A have been fully absorbed.

4. Concluding remarks

Collection of materials for this review began when the editor proposed it in late August 1990, with the author of the opinions (a) that nucleosynthesis was in pretty good shape and (b) that at least some of the worries and puzzles mentioned at the end of Trimble (1975) had been resolved. As these final words are being written (on 25 December 1990 against an end-of-December deadline), these opinions persist. Data on elemental and isotopic abundances in a variety of extra-solar system sites (including supernovae and their remnants) and enormously improved calculations with larger nuclear reaction networks and better cross-sections have, on the whole, made things look better, not worse. The basic process structure, still recognizably that of B²FH and Cameron (1957) stands firm, though incorporating it into a detailed model of galactic chemical evolution remains hampered by our lack of knowledge of which gas clouds will form which sorts of stars and when.

A not very imaginative optimist, looking forward to the next decade or two of nucleosynthesis research, might predict some or all of the following (whose ordering is of only Freudian significance).

- The primordial helium (deuterium, lithium, etc.) abundances will be measured so accurately that we can settle on a unique set of homogeneous hot big bang parameters or rule out this sort of model completely.

- The various proposed x-processes and sites (cosmic ray spallation, hot big bang, AGB star envelopes, novae, supernova shocks, neutrino process...) will have sorted themselves out, though it now seems unlikely that any one will dominate production of all these light, fragile nuclides.

– We will know a good deal more (observationally and theoretically) about absolute and relative abundances in stellar populations other than those in the solar neighborhood.

– The number of physically distinct types of supernovae will have shrunk back to two or three, each with a well-determined (not necessarily simple) set of products.

– Isotopic and elemental abundance anomalies in meteorites will have passed through a stage of even-greater-than-present complexity and come out on the other side into a unified scheme that can be remembered by anyone who knows the first few lines of the periodic table by heart.

– Uncertainties in composition will not be the limiting factor in our calculations of stellar ages, neutrino production rates, or anything else that interests you.

– At least one additional supernova will have exploded close enough to us to verify the calibrations and fine-tuning based on SN 1987A.

– There will be generally accepted answers to (a) the site of the r-process, (b) the cosmic ray source composition, and (c) the $C^{12}(\alpha, \gamma)O^{16}$ rate. Betting on whether these will be the right answers is at longer odds.

– Professors Bethe and Fowler will each be actively investigating some new, imaginative solution to a long-standing problem (not the same one!),

– There will exist an off-the-shelf code for stellar evolution and nucleosynthesis of sufficient completeness, flexibility, and user-friendliness that anyone who wants to can produce the set of models mentioned at the end of the previous section or explore, for instance, the consequences of pretending that there is a stable $A = 8$ nuclide.

Acknowledgements. Papers directly pertinent to nucleosynthesis (or any other major area of astronomy, for that matter) now appear at rates larger than 500 words per minute of the working day. As a result, my opinions on any particular question are increasingly those of some particular expert in the area who is unusually generous about communicating. Those whose views (and frequently preprints) are recognizably present in the present discussion include Danielle Alloin, Edward Anders, W. David Arnett, Ann M. Boesgaard, E. Margaret Burbidge, Geoffrey R. Burbidge, Alastair G.W. Cameron, Robin Clegg, Constantine Deliyannis, Angeles Díaz, William A. Fowler, Bengt Gustafsson, Wolfgang Hillebrandt, Fred Hoyle, Icko Iben, Toshitaka Kajino, David Lambert, Guido Münch, Ken'ichi Nomoto, Bohdan Paczyński, Bernard E.J. Pagel, Ruth C. Peterson, Hubert Reeves, David N. Schramm, Maurice M. Shapiro, Gary Steigman, Friedrich-Karl Thielemann, Beatrice M. Tinsley, Sylvia Torres-Peimbert, James W. Truran, J. Craig Wheeler, and Stanford E. Woosley. It would be unreasonable to hope that every single one of them would be entirely satisfied with the use I have made of their input.

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